Content

Summary

Deep stabilisation is a method to stabilise soft soils by adding dry or wet binders in order to reduce settlements and/or to improve the stability of embankments for roads and railroads. The soil under the embankment can be stabilised either by forming columns of stabilised soil (so-called column stabilisation) or by stabilising the entire soil volume (so-called mass stabilisation). Deep stabilisation can be applied for the stabilisation of various types of soil. In Europe deep stabilisation of soft **non-organic soils** with lime and cement columns has been used in Sweden and Finland for more then 20 years for reduction of settlements and improvement of stability of embankments.

In order to be able to stabilise **organic soils** like organic clay, gyttja and peat research and development was needed. A consortium of companies and organisations from England, Finland, Ireland, Italy, the Netherlands and Sweden has executed a research and development program supported by the European Commission under the Brite-EuRam program of the 4th Framework Program. The acronym of this project was EuroSoilStab. The full tittle: Development of design and construction methods to stabilise soft organic soils for the construction of rail, road and other infrastructure.

In the project full-scale tests are executed in several countries. Column and mass stabilisations are designed and constructed. Embankments are built on top of the stabilisation and the settlements and deformations are monitored to compare with the predicted values. Existing equipment is further developed to cope with wider and deeper columns. Quality control systems are developed and tested on the test sites. New combinations of binders are developed and tested in the laboratory and used for the full-scale tests. All results are combined in this Design Guide.

The EuroSoilStab project has proven that soft organic soils can be stabilised. Organic clay and gyttja gave good results. Peat with high water content asks for special attention. Adding sand to the mix of binders will improve the results. The type and amount of binders can be based on the information given in the Design Guide, but field trials are always needed for the final construction of the stabilisation.

Definitions

Definition	Description
Binder	Binder = Stabiliser = Stabilising agent A binder is a stabilising agent that reacts with the soil and/or the groundwater in a chemical way. Types of binders are: cement, lime, gypsum, furnace slag, fly ash, peat ash, silica fume and other industrial by-products.
Cement-Type Stabiliser	Cement, lime, gypsum, fly-ash and other materials used to chemically stabilize soil
Cohesive Soil	Soil that retains coherence during remoulding
Column stabilisation	Deep soil stabilisation method by means of forming columns of stabilised soil. The stabilisation can be done by a grid of single columns, by overlapping columns forming panels or, for instance, by honeycomb types of structures. Columns up to 25 m can be constructed with the existing equipment.
Deep soil stabilisation	Method to stabilise soft soils (clay, peat or gyttja) by mixing the soil with dry or wet binders in order to reduce settlements and/or to improve the stability
Dosage	The mass of stabiliser in [kg] added to 1 m³ of soil
Dry mixing	Stabiliser is added to the soil in dry state (by air).
ESS	Abbreviation of EuroSoilStab.
EuroSoilStab	Acronym for the European project on soft soil stabilisation by column or mass stabilisation. The full title of the project is: Development of design and construction methods to stabilise soft organic soils for the construction of rail, road and other infrastructure (BE 96-3177).
Exhumation of mixed columns	An oversized casing (preferable a splitable casing) is driven or jetted in to surround the soil mixed column. Casing and column are brought to the surface and laid down. The column is extracted from the casing or the casing is split.
Gyttja	Soil containing a high degree of organic matter originating from remains of plants and animals rich in fats and proteins.
Mass stabilisation	Mass stabilisation is a deep soil stabilisation method by which the entire soft soil volume is stabilised to a certain depth.
Organic soil	Soil that contains organic matter
Peat	Soil containing a high degree of organic matter. Peat is formed by remains of plants rich in carbohydrates that are in various stages in the humification process
Remediation of soil	Remediation of contaminated soil is done by removing the

	polluted soil, by cleaning the soil, by stabilisation of the soil to prevent the migration of pollutants or by the construction of an environmental or geohydrological barrier to prevent pollutants to migrate to or from a soil layer.
Soil stabilisation	See: Deep Soil Stabilisation
Stabilised soil	Soft soil (clay, peat or gyttja) stabilised by mixing the soil with dry or wet binders.
Stabilised soil column	Column of soft stabilised soil.
Stabiliser	See: Binder
Stabiliser components ratio	The ratio (m/m) of the various components of a stabiliser.
Stabilising agent	See: Binder
Water/Stabiliser ratio	The ratio (m/m) of water to stabiliser
Wet mixing	Stabiliser is added to the soil in slurry state (mixed with water)

Symbols

β	Factor for calculation of effective cohesion, c'_k
Δq	Surcharge, kN/m^2
ϕ_k	Characteristic angle of internal friction, degrees
ϕ'_k	Characteristic angle of internal friction in terms of effective stress, degrees
γ	Unit weight, kN/m^3
γ_k	Characteristic unit weight, kN/m^3
γ_f	Partial coefficient for load
γ_m	Partial coefficient for material property
γ_{Rd}	Partial coefficient which takes account of, primarily, the uncertainty in the calculation model
ρ	Density of soil, kg/m^3
σ	Total normal stress, kPa
σ'	Effective normal stress, kPa
σ'_{vo}	Effective overburden pressure, in situ, kPa
σ'_c, σ'_p	Preconsolidation pressure, kPa
σ'_L	Limiting stress, kPa
σ_{ult}	Ultimate strength of column, empirical value, kPa
σ_H	Horizontal stress on columns, kPa
$\sigma_{cr,col}$	Creep strength of column, kPa
τ	Shear stress, kPa
τ_{fd}	Drained shear strength, kPa
τ_{fdk}	Drained shear strength, characteristic value, kPa
τ_{fu}	Undrained shear strength, kPa
τ_{fuk}	Undrained shear strength, characteristic value, kPa
A	Area of cross section of column, m^2
a	Ratio of total column area to total area of reinforced soil
B	Width, m
C_c	Compression index
c	Distance between column centres, m
c'_k	Characteristic cohesion intercept in terms of effective stress, kPa
c_h	Coefficient of consolidation for horizontal flow, m^2/s
c_u	Undrained shear strength, kPa
c_{uk}	Characteristic cohesion intercept, kPa
c_{vh}	Coefficient of consolidation for horizontal flow and vertical deformation, m^2/s
c_{vv}	Coefficient of consolidation for vertical flow and vertical deformation, m^2/s
D	Diameter, m
d_{col}	Diameter of column, m
E_{kcol}	Modulus of elasticity in column, characteristic value, kPa
e	Void ratio
e_0	Initial void ratio
f	Factor of safety with respect to stability failure
f_C	Factor of safety for undrained analysis
f_{unstab}	Factor of safety for unreinforced soil
h	Stratum thickness, m
h_i	Stratum thickness of layer i, m
k	Coefficient of permeability, m/s
k_{soil}	Coefficient of permeability of unstabilised soil, m/s
k_{col}	Coefficient of permeability of column, m/s
L_D	Drainage length, m
M	Modulus, kPa

m	Mass, kg
M' *	Modulus number
M_0 *	Modulus below preconsolidation pressure, kPa
M_k	Characteristic value of compression modulus, kPa
M_L *	Compression modulus, kPa
M_{soil}	Compression modulus in soil, kPa
M_{col}	Compression modulus in column, kPa
m_s	Mass, solid particles, kg
n	Ratio of influence radius of column to column radius (R/r)
q	Surcharge, kN/m^2
q_1	Load carried by single column, kN/m^2
q_{1max}	Maximum load carried by single column, kN/m^2
q_2	Load carried by unstabilised soil, kN/m^2
R	Influence radius of column, m
r	Column radius, m
s_1	Settlement in column, m
s_2	Settlement in unstabilised soil, m
S_{eff}	Stabilisation effect, ratio of shear strength of stabilised soil to shear strength of unstabilised soil
S_m	Calculated settlement, m
S_t	Sensitivity
t	Time of consolidation, s, year
u	Pore water pressure, kPa
U	Degree of consolidation
V	Volume, m^3
$V_1, V_2 ... V_n$	Volumes, m^3
w_L	Liquid limit, %
w_n	Natural water content, %
z	Depth below reference surface, m

Indices

x_d	Design value of parameter x
*	For explanation of the parameters, see Chapter 4

1. Introduction

1.1 Scope of the design Guide

This Design Guide for deep soil stabilisation of soft organic soils deals with all the aspects of the application of column and mass stabilisation:

- the soil investigations in situ and in the laboratory;
- the design of the mixture of binders;
- the design of the stabilisation;
- the construction of the stabilisation;
- the inspection of the stabilised soil.
- the inspection of the behaviour of the stabilisation.

The Design Guide is a description of the best practice, mainly based on the experiences at seven test sites of the European project EuroSoilStab. This project is executed in the period February 1997 until September 2000. The test sites were located in Finland (2), Sweden (2), United Kingdom (1) and the Netherlands (2).

1.2 Users of the design guide

The design guide is meant as a guide for all parties involved in the use of the deep soil stabilisation technique. The client can find the solution for his construction problem and can learn the principles of the deep stabilisation methods. The engineer will be guided in the design activities for the column or mass stabilisation and the design of an optimal mixture of binders. The engineer can also find what soil investigations are necessary or useful in situ or in the laboratory to support the design activities. The contractor will find information about the equipment needed for the stabilisation of the soil. Also the construction methods are dealt with and quality assurance procedures. A chapter deals with inspection and is of use for the client, the engineer and the contractor.
Furthermore, the design guide can be of use for education purposes.

1.3 Acknowledgement

This design guide is mainly based on the results of the European RTD-project EuroSoilStab. The European Community under the Industrial & Materials Technologies Programme (Brite-EuRam III) for 50% funds this project. The rest of the funding comes from the partners in this project:

- Helsinki City Public Works Department
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- Viatek Ltd.
- Building Research Establishment
- Keller Limited
- Trinity College Dublin Department of Civil, Structural & Environmental Engineering
- Università degli Studi di Padova, Dipartimento di Ingegneria Idraulica, Marittima e Geotechnica
- CUR, Centre for Civil Engineering Research and Codes
- GeoDelft
- Fugro Ingenieursbureau BV
- Nederhorst Grondtechniek BV (nowadays: HGB Civiel Grondtechniek)
- NS Railinfrabeheer Projectorganisatie HSL-Zuid Infra
- Rijkswaterstaat Directorate General for Public Works and Water Management
- Swedish Geotechnical Institute
- Stabilator (nowadays: Skanska Grundläggning)

All partners express their thankfulness to the European Community for the financial support. They also express their gratitude towards each other for the pleasant and fruitful co-operation.

2. Principles of deep stabilisation

2.1 Introduction

Deep stabilisation is a method to stabilise soft soils by adding dry or wet binders in order to reduce settlements and/or to improve the stability. he soil can be stabilised either by forming columns of stabilised soil (so-called column stabilisation) or by stabilising the entire soil volume (so-called mass stabilisation). However, the two methods may well be combined as shown in the example, figure 2.1. With existing equipment the soil can be stabilised to a depth of about 25 meters when using column stabilisation whereas mass stabilisation can be used to a depth of about 5 meters.

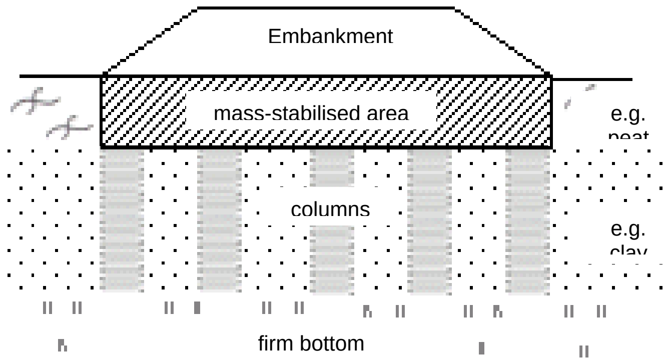


Figure 2.1. The schema of a structure combining mass and column stabilisation.

The main purposes of deep soil stabilisation are:

a) To increase the strength of the soft soil in order to:
   - increase the stability of an embankment
   - increase the bearing capacity
   - reduce the active loads on retaining walls
   - prevent liquefaction

b) To improve the deformation properties of the soft soil in order to (static loads) reduce the settlements in order to:
   - reduce the time for settlements
   - reduce the horizontal displacements

c) To increase dynamic stiffness of the soft soil in order to:
   - reduce the vibrations to the surroundings
   - improve the dynamic performance

d) To remediate contaminated ground (soil) by:
   - creating an environmental barrier (solidification)
   - stabilisation of the contaminated ground
   - creating a geohydrological barrier

2.2 Applications

2.2.1 Binders in different soil types

Deep stabilisation can be applied for the stabilisation of various soft soils like clay, gyttja and peat. However, the geotechnical and chemical properties of the soil to be stabilised will affect the results of stabilisation and the choice of the appropriate binders.

The binder can be installed either by a “wet method”, where a slurry of binder and water is used, or by the “dry method”, where the dry powder reacts chemically with the pore water during curing. Therefore, the dry method reduces the water content of the soil.
2-component binder mixes are widely used but 3-component binders are more versatile and can be more effective for many cases. The most important components are limes, cements, blast furnace slag and gypsum. In regard to the use of industrial by-products also high quality fly ashes can be exploited for certain cases, especially in the stabilisation of peat.

2.2.2 Types of applications

The mass and column stabilisation can be applied in many different ways. Figure 2.2 gives some examples of the configuration of columns. Figure 2.3 suggests some applications for the combined mass and column stabilisation.

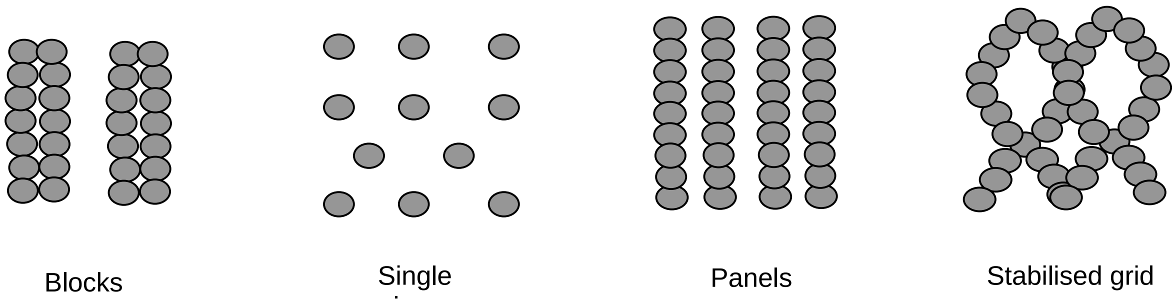


Figure 2.2a. Examples of the placing of columns.

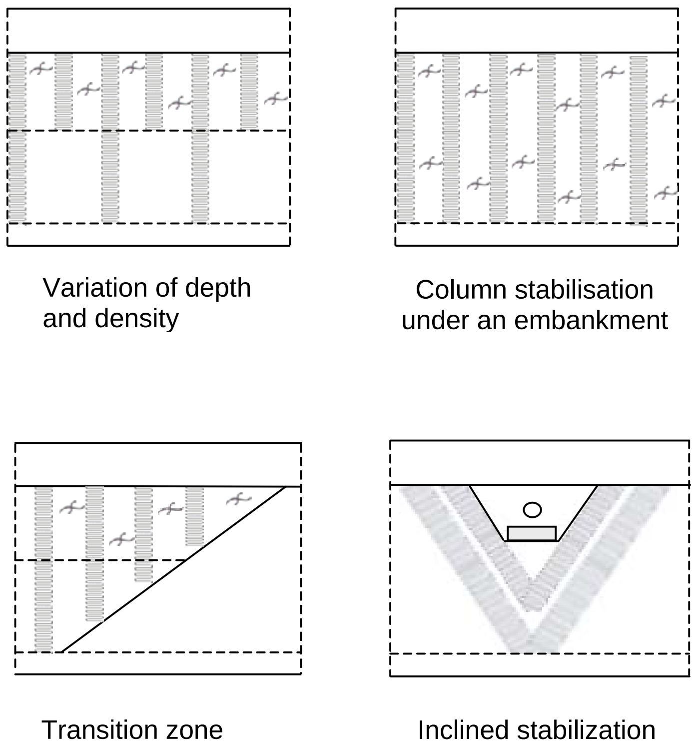
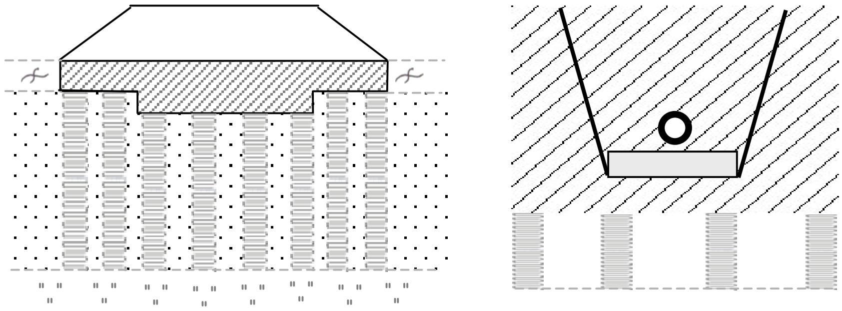


Figure 2.2b. Examples of placing of columns.

Figure 2.2. Examples of configurations for column stabilisation.



Embankment with mass and column stabilisation

Pipe line with mass and column stabilisation

Figure 2.3. Principle applications of combinations of column and mass stabilisation.

2.2.3 Comparison with other stabilisation methods

The main advantages of deep stabilisation are:

- economic
- flexibility
- savings of materials and energy
- rapidity
- can be flexibly linked with other structures and with the surroundings (no harmful settlement differences)
- flexible improved engineering properties of the soil

In figure 2.4 soil improvement using deep stabilisation and some alternative methods are compared and their relative merits and drawbacks are listed.

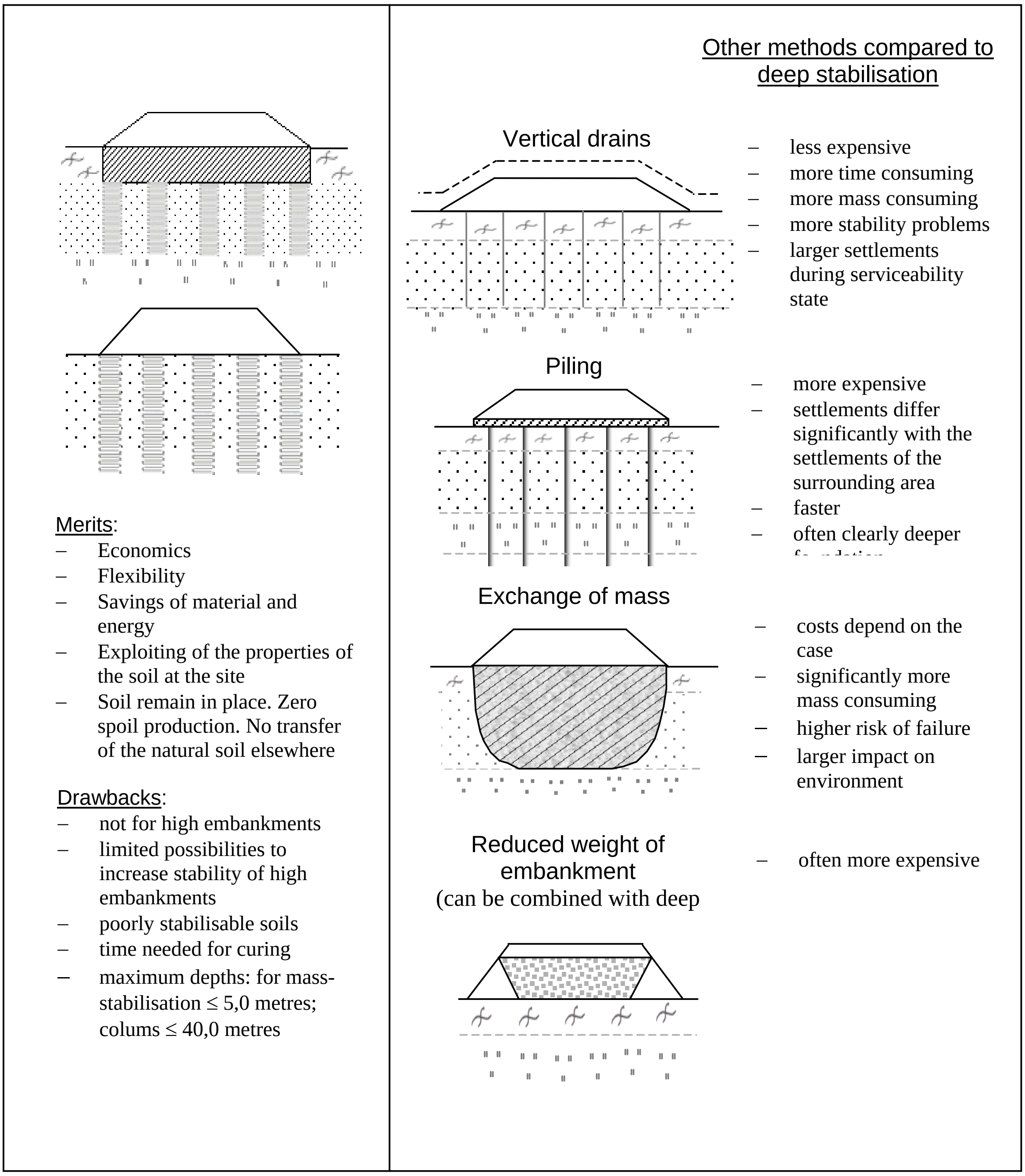


Figure 2.4. Deep stabilisation compared with some other methods.

2.3 Construction

Mixing mechanically a binder and soil with a mixing head having a nozzle for binder feeding carries out the deep stabilisation procedure. The mixing tool is connected to a rotating kelly of the deep stabilisation machine. Different types of mixing tools exist, usually they are 0,5 – 0,8 meters in diameter. A typical equipment for column stabilisation is shown in figure 2.5.
For example at the “dry method” of column stabilisation the construction normally starts by penetrating the rotating shaft and the mixing tool down to the target depth. After this the mixing tool is lifted while simultaneously feeding the binder. As a result a column of stabilised soil with a circular cross section is formed. The maximal column length is about 40 meters with existing equipment.

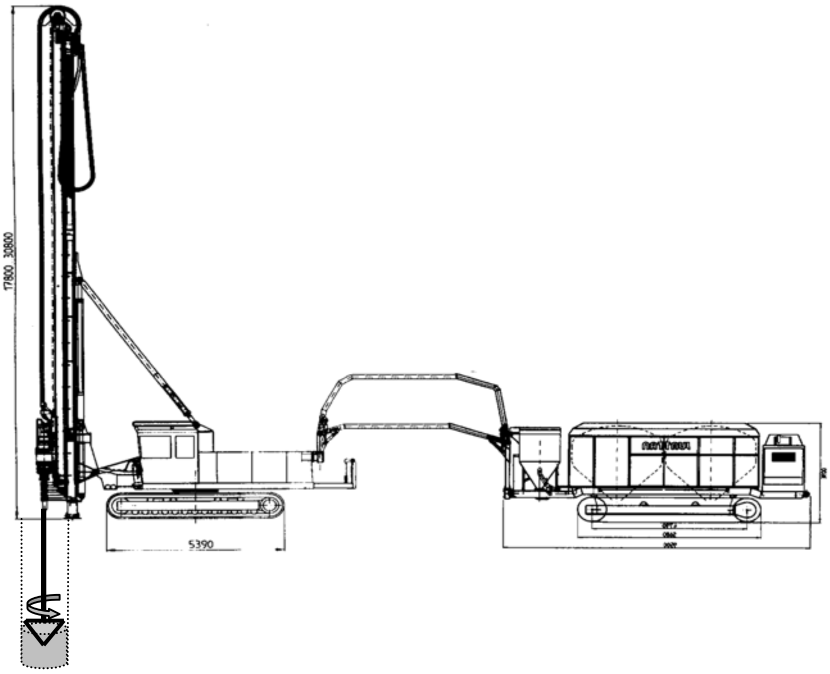
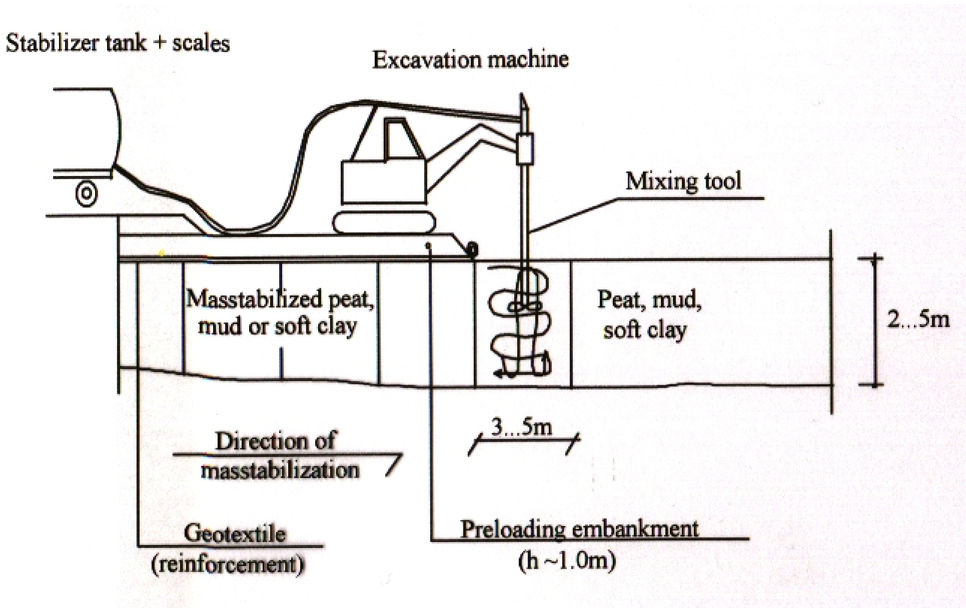


Figure 2.5. Typical equipment for column stabilisation.

Depth 15-24 m (max), rotating speed 100-200 r/min, lift of the rotating tool 10-25 mm/r.

The mass stabilisation machines essentially differ from the column stabilisation machines. Mostly the mass stabilisation machine is a conventional excavator but equipped with a mass stabilisation mixer. The binder is fed to the mixing head while the mixer rotates and simultaneously moves vertically and horizontally. Two different types of mass stabilisation technology are shown in figure 2.6. Mass stabilisation can also be made with column stabilisation equipment making overlapping columns.
Environmentally, the column and mass stabilisation have only minor effects. Vibration and noise are low. Leaching and transport of harmful substances due to binder materials will be insignificant.



TYPE A

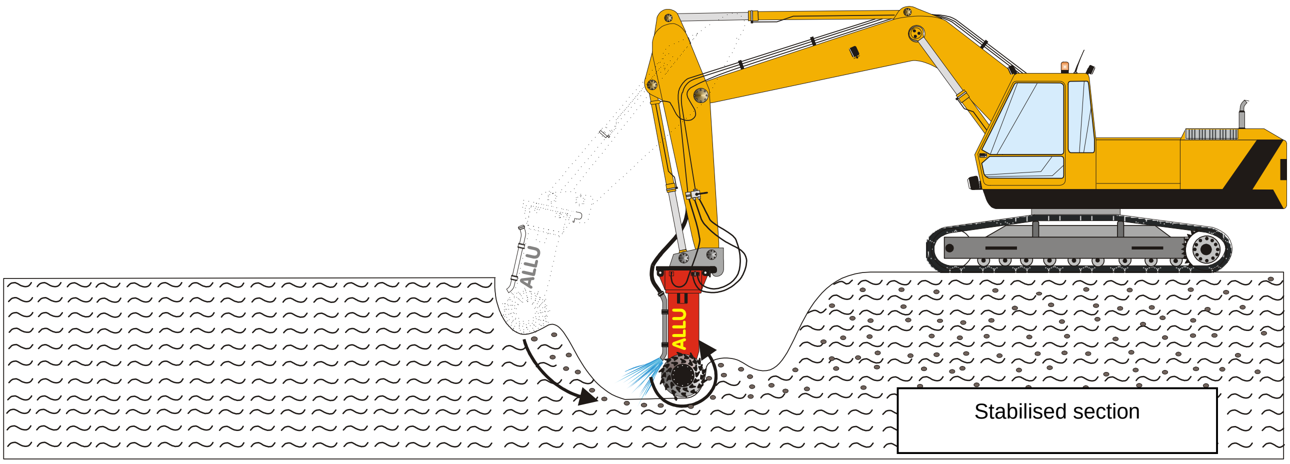


Figure 2.6. Mass stabilisation technology.

2.4 Properties of stabilised soft soils

As a result of stabilisation, the chemical and physical properties of clay, gyttja and peat will significantly change. The pH-value of the stabilised soil will quickly rise up to 11 – 12 and the curing will start. Depending on the type of binder some of the chemical reactions will take place relatively quickly (during the first month) but some of the reactions may develop more slowly; and may take months or even years.

The strength of the stabilised soil depends on the type and quantity of binder as well as the properties of the natural soil. Additionally, the homogeneity of the mixing clearly affects the resulting strength. However, the undrained shear strength of stabilised soil is normally within the range of 50 – 150 kPa. It should be noted that laboratory prepared samples of stabilised soil may have an undrained shear strength of several hundreds of kPa but such high values are rarely obtained in situ.

The relation between the curing time and the strength of the stabilised soil is important since it governs the acceptable rate of loading. This relation depends on the soil type and the type of binder. However, when using only cement most of the strength develops during the first month after stabilisation. When using binders including lime, gypsum, furnace slag and/or ash the strength will still continue increasing after the first month. Therefore, thorough investigations make it possible to optimise the time schedule for the construction, as schematically shown in figure 2.7:

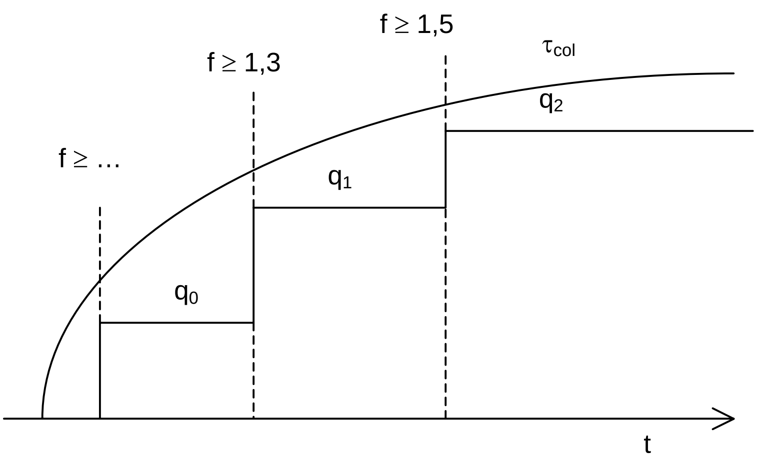


Figure 2.7. Optimisation of the curing time and the load on the embankment.

Symbols of the figure:

τ_{col} = shearing strength of columns

q_0 = load/overburden pressure at pre-compaction

q_2 = load/overburden pressure of the final structur

f = F = safety factor with respect to stability

q_1 = load/overburden pressure of the embankment

t = time

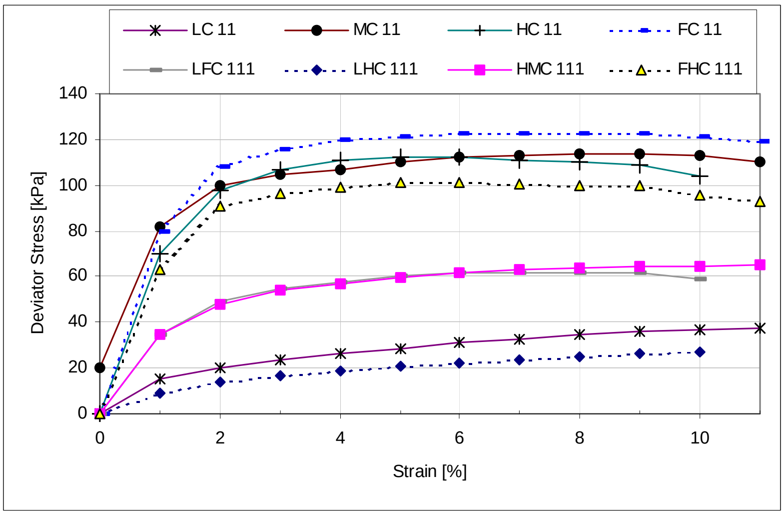
2.5 Chemical and mechanical interaction of the stabilised and natural soil

When mixing the binder with soil the chemical reactions start immediately. When cement is used a stabilising gel between the soil granules is created due to pozzolanic reactions. A very homogeneous mixing is required since cement, unlike lime, does not diffuse.

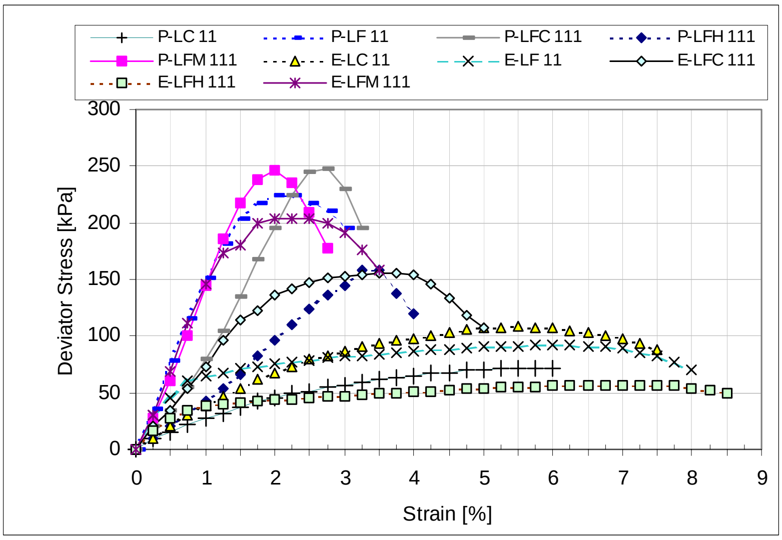
When using pulverised binders based on lime the soil reactions continue for several months:

- the water content of the soil decreases since water is consumed during the chemical reactions;
- the lime reacts with the clay minerals;
- calcium ions will diffuse from zones of high binder concentration both within the stabilised volume and to adjacent zones originally not involved in the mixing. Consequently, the homogeneity and strength of the stabilised volume is improved.

The geo-mechanical properties of the stabilised material largely depend on the type of binder. In general, the strength and brittleness of the stabilised soil increase with increasing amount of cement. On the other hand, the ductility will increase with increasing amount of lime. Typical stress-strain relations for different stabilised soils using different types of binders are shown in figure 2.8.



a. Stress-strain of stabilised peat



b. Stress-strain of stabilised gyttja

Figure 2.8. Stress-strain curves of stabilised soil.

Figure 2.8.a. Examples of peat from Kivikko (Helsinki, Finland), and of gyttja from Porvoo (P-; Finland) and Enånger(E-; Sweden) Figure 2.8 b. Symbols of binders: L=lime, C=cement, F=Finnstabi®-gypsum, M=blast-furnace slag, H = a Finnish fly ash and V= a Swedish fly ash . Numbers indicate the proportion of components. The tests have been performed in 1997.

The underlying design philosophy for deep stabilisation is to produce a stabilised soil that mechanically interacts with the surrounding unstabilised soil. The applied load is partly carried by the columns and partly by the unstabilised soil between the columns. Therefore, a too stiffly stabilised material is not necessarily the best solution since such a material will behave like a pile. Instead, the increased stiffness and strength of the stabilised soil should not prevent an effective interaction and load distribution between the stabilised and natural soil. This philosophy is schematically described in figure 2.9.

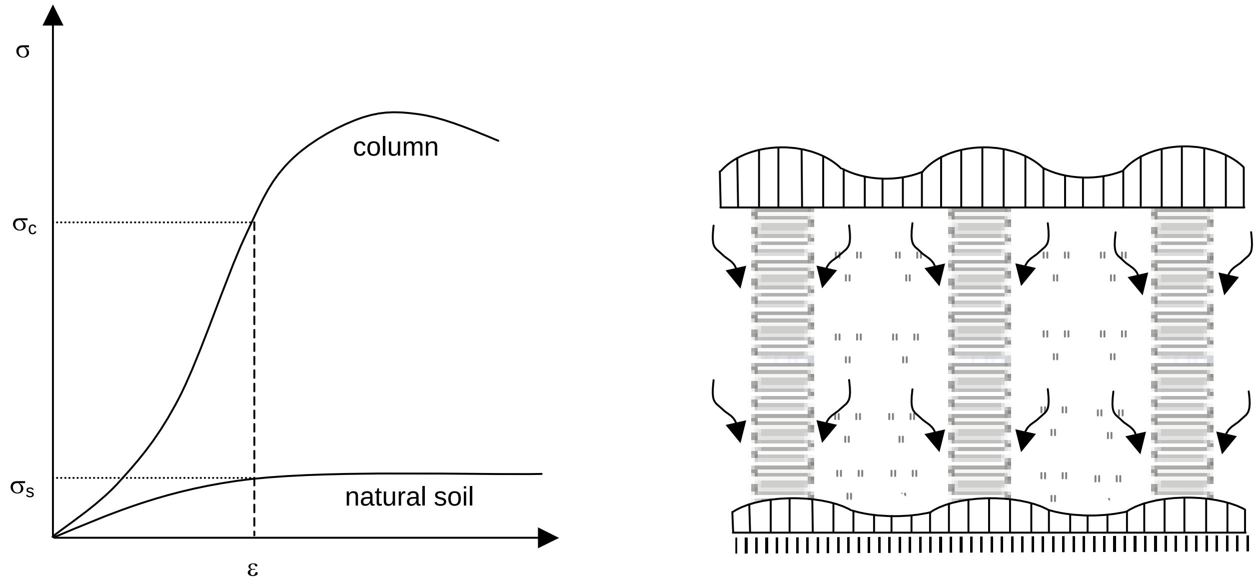


Figure 2.9. The geo-mechanical design philosophy for deep stabilisation.

3. Examples of structures suitable for stabilisation work

3.1 Introduction

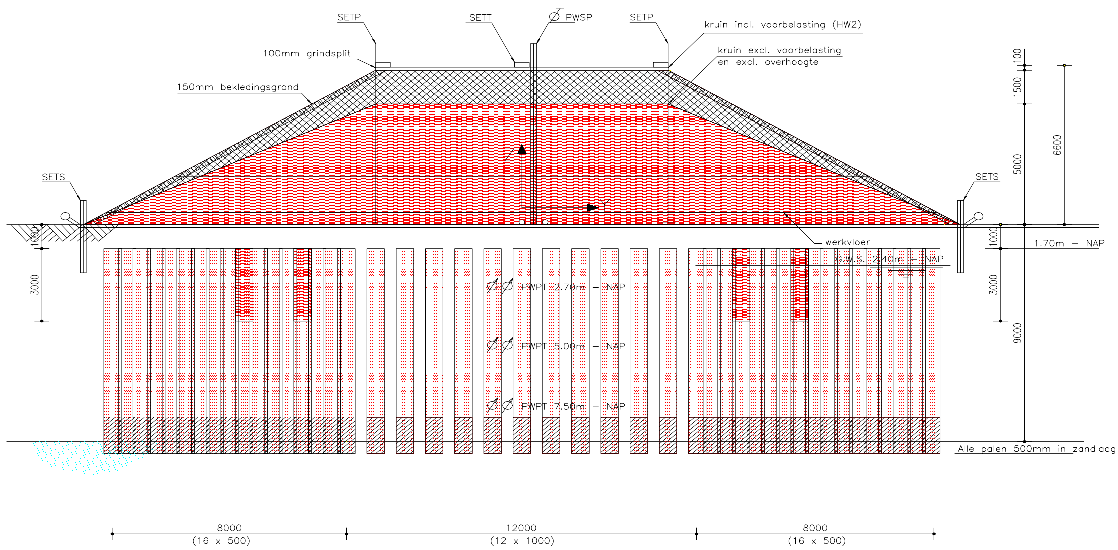
In the previous chapter a general outline is given on the principles of deep stabilisation. In this chapter applications will be described in which soil stabilisation is applied. For the first three functions examples are given in the next paragraphs.

3.2 Examples for road and railway embankments

Deep soil stabilisation is widely used for the foundation of road and railway embankments.
For the Dutch high speed rail link an alternative design has been made using deep soil stabilisation. The design was tested on a test site. The embankments for this substructure of the rail system is constructed on 9 meter very compressible subsoil. The subsoil consists of organic clay and peat. The compressible layers lie on a stiff and bearing sand layer. The test-embankment has a high and a low part. The high part is 5 meter high, the low part is 1 meter high. The high part of the embankment ends at an imaginary piled bridge foundation. In the sub-structure system the designers incorporated a transition zone to control the differential settlements of structure and embankment.
The foundation of the embankment consists of stand-alone stabilised soil columns and panels for the high part and a combination of mass stabilisation on the top of stand-alone columns in the low part. The mass stabilisation (performed as overlapping short columns) was made to a depth of 2 meters. The columns were made down to the bearing sand layer: the tip of the column is fixed. The columns have a diameter of 600 mm and were installed in a square pattern. The centre to centre distance varies from 1.0 meter for the high part of the embankment near the imaginary bridge up to 1.6 meter under the mass stabilisation for the low embankment.

In figure 3.1 Plan and cross-section for high and low embankment respectively are presented.

HW2 high embankment, cross-section



Annex 2.2

Figure 3.1. Plan and cross-section for high and low embankment for the Dutch High Speed Link.

The deep soil stabilisation method has the potential to be designed according to the specifications reflecting about total and differential settlements at the connection point of bridge and the approach embankments and reflecting the soil conditions, as shown in figure 3.2 below. In some cases a reduction of the amount of stabilisation can be achieved by using different length of columns. This is especially applicable when the soil properties improve with depth.

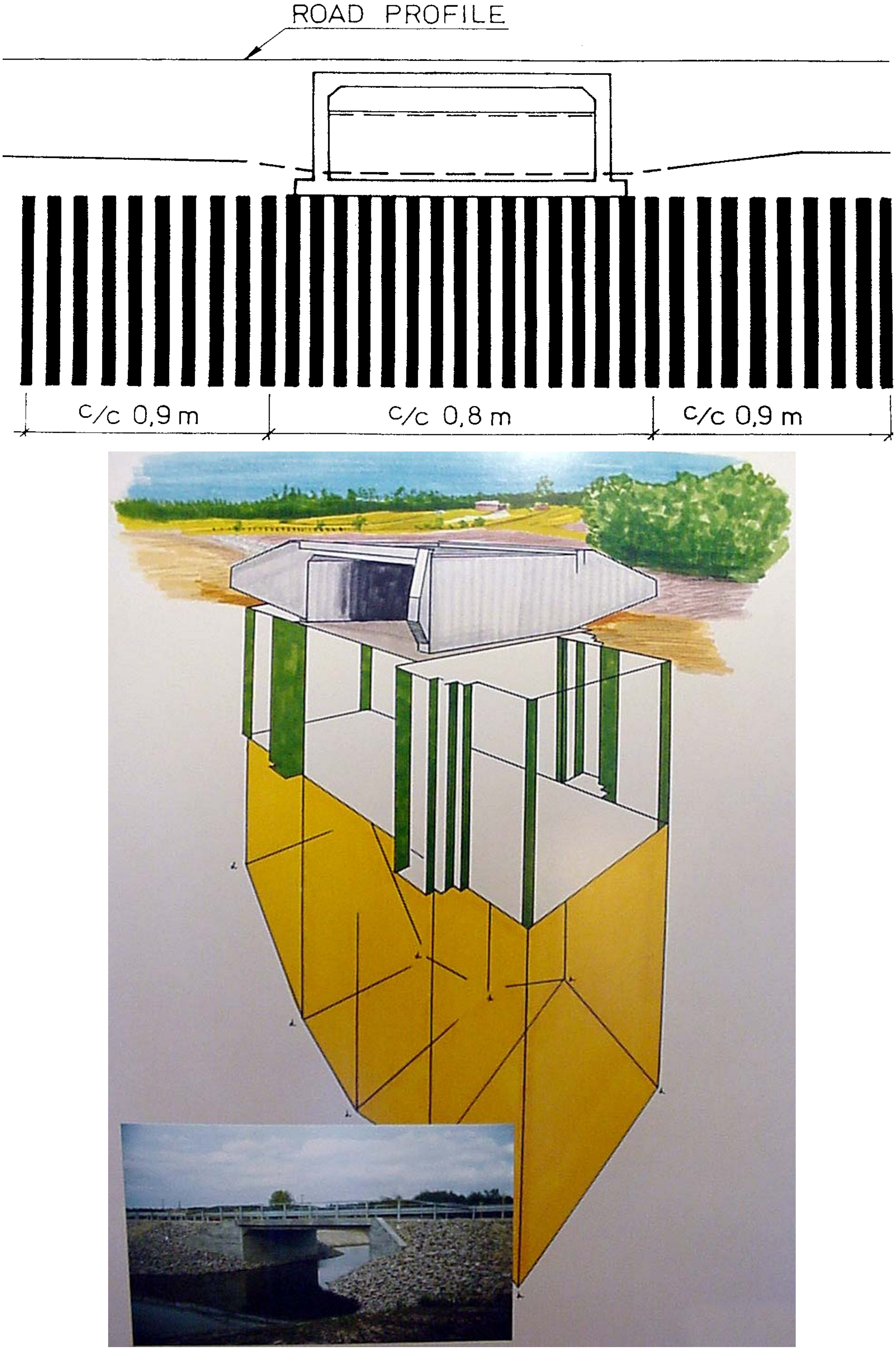


Figure 3.2. Deep soil stabilization for a bridge and the approach embankments in Sweden.

Mass stabilisation is primarily used to stabilise very soft soils, primarily peat. The total soil volume is mixed in a horizontal and vertical direction. The stabilised block is much stiffer than the original soil and will not only reduce the settlements but also improve the stability. In figure 3.3 a typical cross-section is given. This application applies in case of a limited depth (< 5 m) of the layers with a sufficient bearing capacity.

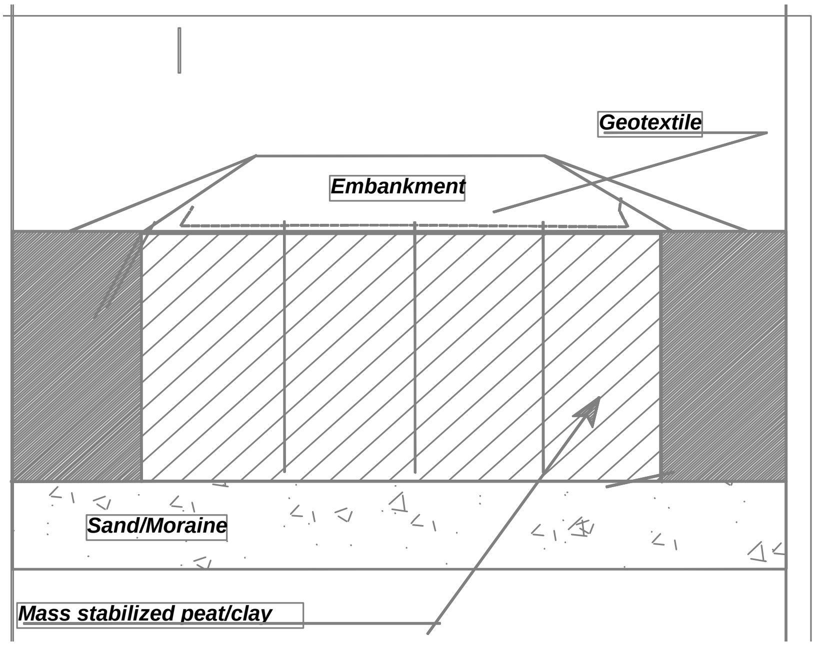


Figure 3.3. Typical cross-section of mass stabilisation for an embankment.

3.3 Slopes

Another application of deep soil stabilisation is a stabilisation of slopes. This can be done using panels, a grid of panels or mass-stabilisation. The design has to withstand all the forces acting on the stabilised area. During installation special attention has to be given to the pore pressures and movements, because of the unstable character of the site. An example is shown in figures 3.4 and 3.5. An example of a stabilized cut is shown in figure 3.6.

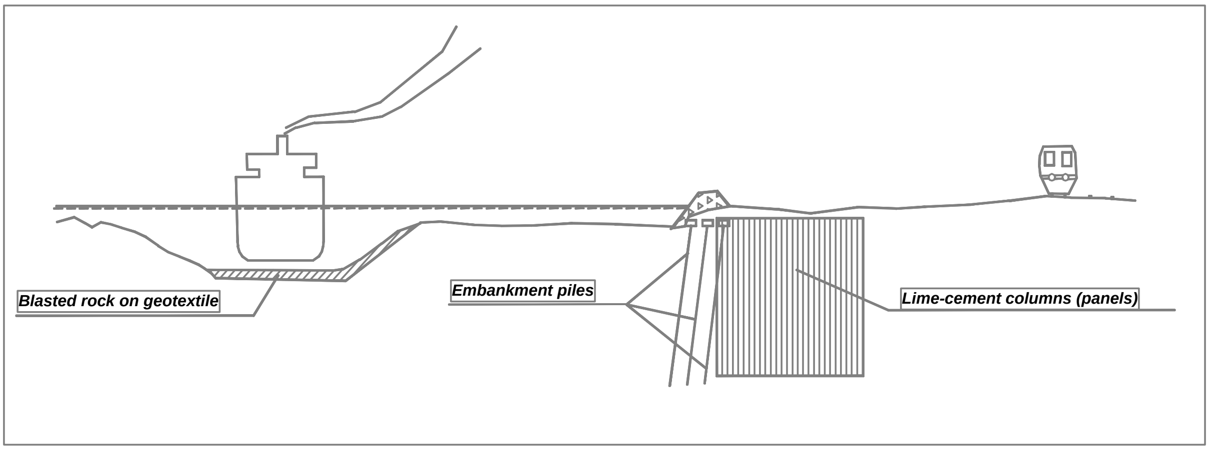


Figure 3.4. Stabilised slope at Agnesberg, Sweden.

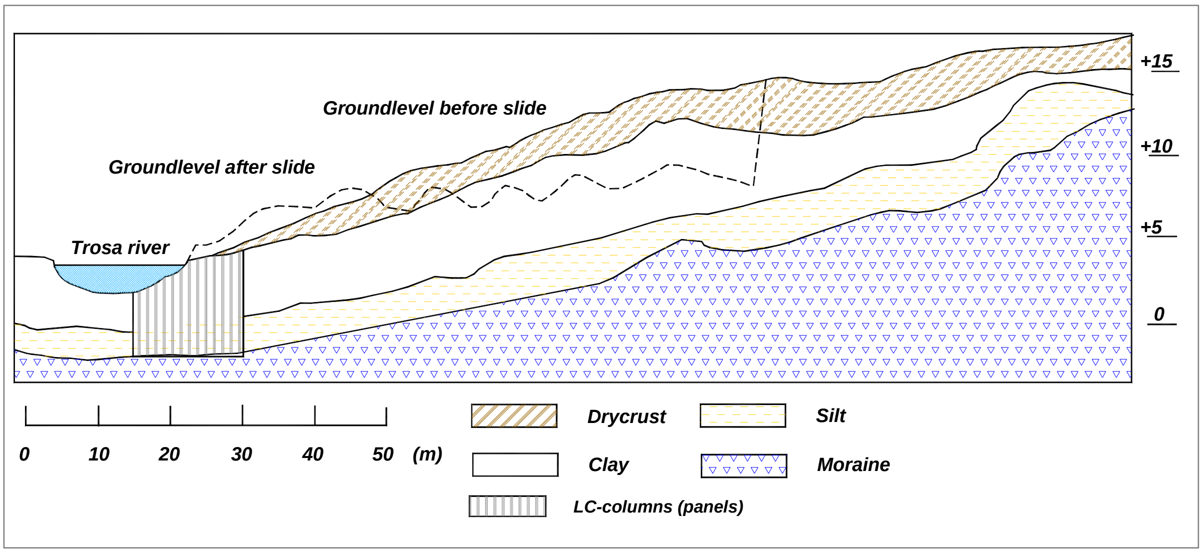


Figure 3.5. Stabiliswed slope near the Trosa river, Sweden.

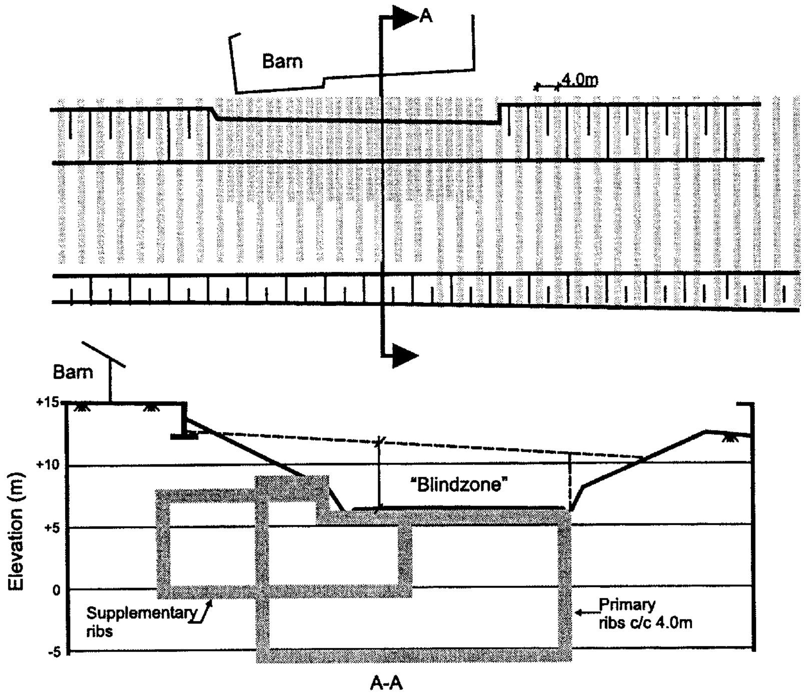


Figure 3. 6. Example of stabilized cut.

3.4 Seismic mitigation

Figure 3.7 shows an example of column panels to prevent liquefaction mitigation in California, USA. This is not related to organic soils but silt and silty sands. In areas where seismic activity can be expected soil stabilisation can be used to prevent liquefaction. The main aim of the stabilisation is to reduce pore water pressures or to increase the shear strength of soils that could liquefy.

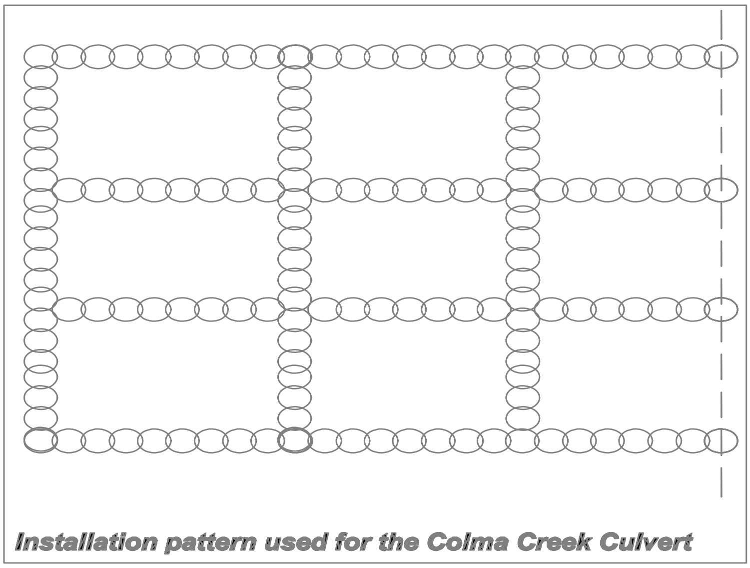


Figure 3.7. Example of panels to prevent liquefaction mitigation in California, USA.

3.5 Vibration reduction

Soil stabilisation can also be used in cases where reduction of vibrations is required. Vibrations can be caused for example by trains, heavy traffic or construction activities. In case of constructing high speed railways over soft soils special attention has to be given to the propagation of the shock waves in the super- and substructure of the rail system. Soil stabilisation can be applied to achieve a sufficient dynamic performance of the rail system, figure 3.8. In figure 3.9 an application of the high speed line in Sweden is presented.

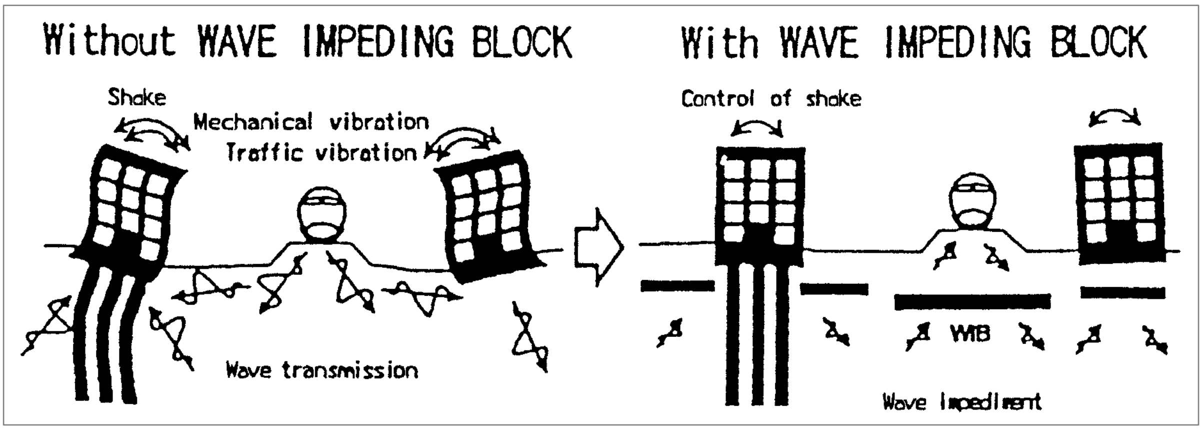


Figure 3.8. Wave impeding block method for vibration reduction.

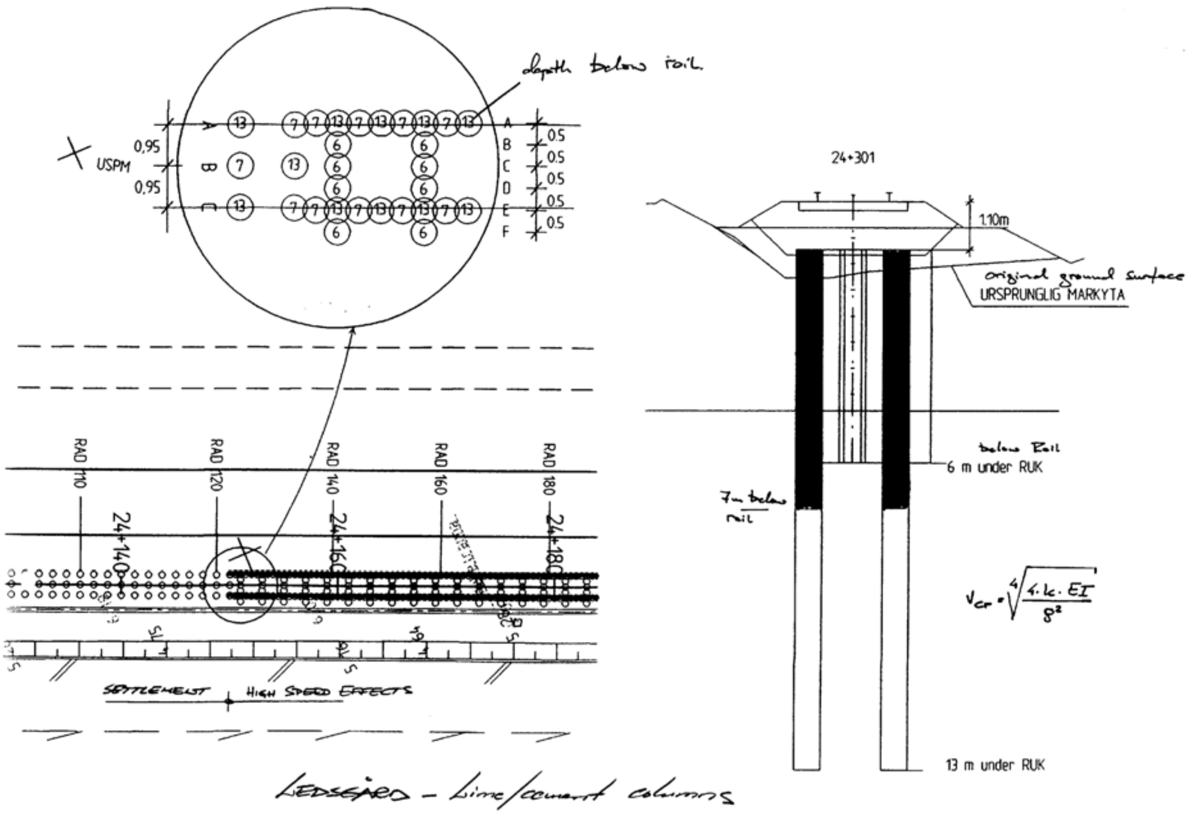


Figure 3.9. Example of deep stabilization for a high speed line.

3.6 Miscellaneous

Deep soil stabilisation can be applied in many other ways, such as:

- foundations for buildings and bridges;
- isolation of contaminated soils;
- protection of adjacent structures;
- reduction of earth pressure;
- stabilisation of very soft soils for tunnel boring.

Due to the increasing experience and results from research programs and development of the equipment new applications will arise in the near future.

4. Design methods

4.1 Design requirements

The stabilised ground must be designed and executed in such a manner that, during it will remain fit for the use for which it is required and will sustain all actions and influences likely to occur during the execution and use. This should apply for the appropriate degrees of reliability and in an economic way. This requires that the stabilised soil satisfies ultimate and serviceability limit states.
The requirements for the serviceability and ultimate limit states and for service life are to be specified by the client. The design is to be in accordance with the requirements of Eurocode 7 or national regulations are applied.
The design method presented in this document is based on the prestandard version of Eurocode 7, ENV 1997-1. In accordance with the Eurocode philosophy in relation to soil parameter values a distinction is made between:

- Measured values
- Derived values
- Characteristic values
- Design values

The derived value is the value of a ground parameter obtained by theory, correlation or empiricism from the measured test results. A characteristic value is determined from the derived values to give a cautious estimate of the value affecting the occurrence of a limit state. This terminology will be used in the following section of the Design Guide.
The determination of the derived and characteristic values shall be in accordance with the principles of Eurocode, subject to the restrictions on the characteristic values of some parameters recommended in this Design Guide.

4.1.1 Service life

The stipulated service life is stated in construction specifications (Cf. Eurocode 7 and National Regulations).

4.1.2 Limit states

The design of stabilised ground must satisfy ultimate and serviceability limit states.
To satisfy ultimate limit state (ULS) requirements, the design of the stabilised ground must be such that there is a low probability of collapse of the supported structure. This includes failure due to prior excessive deformation in the ground or a risk of danger to people or severe economic loss.
A column stabilisation and a mass stabilisation is designed to give the structure or embankment and its close surroundings satisfactory overall stability, so that failure of the structure or a part of this is not caused by large deformations
(Cf. Eurocode 7 and National Regulations).
As stated above, the design method presented in this document is based on the prestandard version of Eurocode 7, ENV 1997-1. This version of EC 7 requires that three design situation should be considered in ULS analysis, namely Cases A, B and C.
Case A mainly refers to buoyancy problems and must be considered when this relates to the particular design situation under consideration. The general application of this Case A will not be discussed in this Design Guide.
Case B relates to the strength of structural elements and is therefore not applicable to stabilised soil itself. Case B will not be discussed further, although there may be cases involving stabilised soil/structural interaction in which this case would be applicable.
Case C governs the safety margins against failure of the soil and is relevant to limit state analysis of stabilised soil. The following discussion therefore mainly relates to Case C.
To satisfy serviceability limit state (SLS) requirements, column stabilisation and mass stabilisation, including transition zones to unstabilised embankments shall be designed in such a way that the total and the differential settlements along and across the road surface satisfy the requirements in Eurocode 7 or national regulations. The SLS must include consideration of long-term creep movements.

4.1.3 Durability

The choice of characteristic material values should consider the durability of the deep stabilisation.

4.2 Design principle and philosophy

The design is carried out for the most unfavourable combination of load effect and bearing capacity, which is likely to occur during construction and in service.
Design models are based on the assumption of interaction between columns and unstabilised soil, which implies that the design models are valid only for semihard columns with a maximum shear strength of 150 kPa.

Design of the preloading stage is based on characteristic values. When using the observational method, for example deviations from the predicted settlements will provide a basis for the decision whether a temporary surcharge can be removed (see fig. 4.1), the surcharge must be increased or the preloading period should be extended.
The design should be based on column strength from field tests.

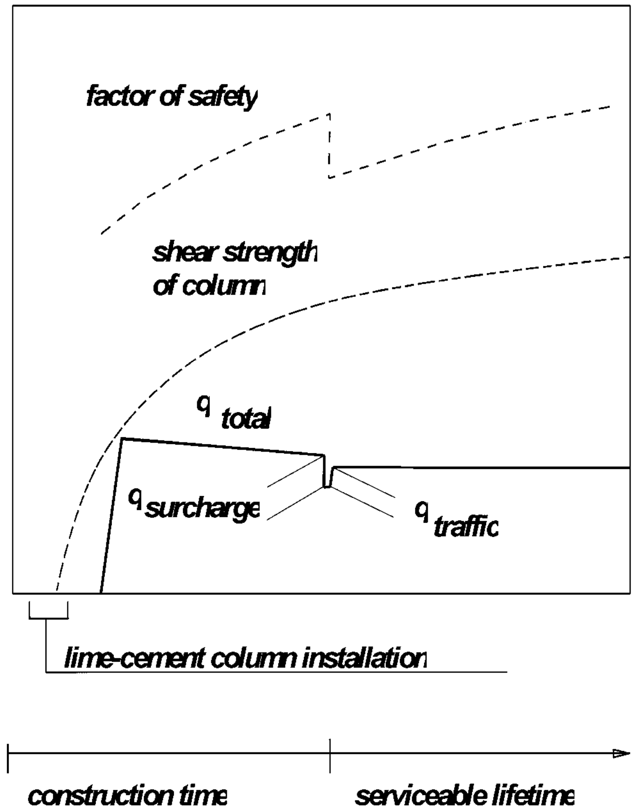


Figure 4.1. Preloading by surcharging.

4.2.1 Ultimate limit state, ULS

The ULS mechanisms to be considered in the design of stabilised soil columns are to include failure of the column itself and overall failure through the columns and the untreated ground.
The design parameters for ULS shall be based on the characteristic values divided by an appropriate partial factor. Eurocode permits the use of partial factors lower than those given in EC 7 for certain temporary conditions. This Design Guide gives recommendations on the appropriate partial factor to be used under such conditions in the design of soil stabilisation.

4.2.2 Serviceability limit state, SLS

SLS calculations are carried out using characteristic values of parameters.
Settlement calculations should also be based on the assumption that the distribution of load between columns and unstabilised soil is on the basis that at every level the same compression occurs in columns and in the unstabilised soil.

Deep stabilisation should be combined with preloading including a temporary surcharge. The purpose of surcharge is to consolidate the soil for a load higher than the service load. The surcharge should be

designed so that parts of it can be removed at the end of the preloading period. This will reduce or eliminate future creep settlements.
In design it is presupposed that a settlement calculation is performed. This calculation is a basis for a prognosis of the settlements during the construction stage and the service stage respectively.
A careful follow-up (e.g. settlements, pore pressures) during the construction stage is essential for verifying the behaviour. The deep stabilisation method shall be used together with active design (observational method).

4.2.3 Column stabilisation

The term semi-hard column refers to columns with a maximum characteristic shear strength of 150 kPa.
Calculation models presented in this publication assume interaction between columns and unstabilised soil.

Full interaction between columns and the intermediate unstabilised soil is assumed to occur if there are no initial ongoing movements in the natural ground where the structure is to be built. Road and railway embankments are often stabilised with single (isolated) columns in a square pattern. For an average value of the shear strength, stability can be calculated on the basis of cylindrical slip surfaces. This can be done provided that these columns are axially loaded, which applies for the active part of the slip surface, and that the maximum characteristic value of the undrained shear strength of the columns (c_{uk}) is put at 100 kPa (in favourable cases 150 kPa, see 4.8.2). For a heterogeneous sequence of strata, however, planar and composite slip surfaces may constitute the design criterion.

Single columns in the direct shear zone and passive zone shall not be used since interaction can not be assumed. In order to ensure interaction in the direct shear zone and passive zone, the columns are placed in panels, grids or blocks. Stability is always calculated by combined and undrained analysis. Combined analysis means that the lowest value of drained or undrained shear strength is selected for each section of the slip surface, see 4.8.2.
The maximum characteristic value of undrained shear strength, c_{uk}, of columns is put at 150 kPa irrespective of possible higher values of laboratory and field trials. Note that in many cases it is difficult to reach as high values in field as in laboratory tests. For purposes of stability calculation, see 4.8, c_{uk} is in some cases limited to 100 kPa.

4.2.4 Mass stabilisation

In design a mass stabilised soil is assumed to be a homogeneous elasto-plastic soil layer. The uncertainties of the result of mixing and homogenisation of the stabilised soils must be considered in the design. Note that in many cases it is difficult to reach as high values in field as in laboratory tests.

4.3 Geotechnical category

GC3 Column stabilisation is carried out in Geotechnical Category 3 (Cf. Eurocode 7 and National Regulations).

4.4 Geotechnical investigation

Field and laboratory investigations shall provide information regarding:
- sequence of soil layers and their properties;
- groundwater conditions;
- the presence of organic soil, sulphides in the soil and pH;
- the composition, thickness, firmness of the surface stratum and any tree roots, fill, etc;
- the presence of fixed obstacles to column placing (e.g. buried pipes, cables and overhead lines);
- -the properties of soil after the binder has been mixed in. Mixing trials are performed for characteristic soil strata, see 6.4.

4.5 Loads

The loads are specified by the client (Cf. Eurocode 7 and National Regulations).
Calculation of stability during construction phase (building of embankment) often yields the lowest factor of safety. Traffic load during construction can be restricted by agreement with the client. The restrictions are set out in construction specifications.

4.6 Characteristic material values

4.6.1 General

Characteristic values are set out in construction specifications and are chosen as cautious selected values taking the design situation into consideration.
Soils react in different ways to chemical stabilisation. The mixing trials in the laboratory indicate whether the soil can be stabilised. The stabilisation effect in the field may be appreciably different from that in the laboratory.

4.6.2 The strength and deformation properties of soils

Soil properties shall be determined by investigations in the laboratory and/or in the field. Laboratory tests, field tests and parameters of unstabilised soil are given in Chapter 5.

4.6.3 Unit weights and strength and deformation properties of stabilised soil

Characteristic values of stabilised soil properties shall primarily be based on field tests on trial columns and/or trial pads. Characteristic values of column properties and mass stabilisation properties may also be based on the results of laboratory tests made on specimens mixed in the laboratory. Characteristic values based on laboratory mixed samples should consider the difference between laboratory and field strength. For the performance of laboratory tests, see 6.4.

γ_k, the characteristic unit weight of stabilised columns is put equal to that of unstabilised soil.
γ_k of mass stabilisation shall be based on results from laboratory tests made on specimens mixed in the laboratory.

c_{uk}, the characteristic value of undrained shear strength is primarily based on the results from field tests on trial stabilisation. Or, if applicable, on unconfined compression test on specimens mixed in the laboratory considering the difference in strength between laboratory mixed samples and field columns. The maximum value of c_{uk} in stabilised columns is however
150 kPa, irrespective of the results of laboratory and field tests. Because of the uncertainties in mixing and unequal spread of binder in mass stabilisation the characteristic value of undrained shear strength in mass stabilisation must be determined very carefully.

E_k, the characteristic value of Young's modulus in lime-cement columns is put equal to 50-100 c_{uk}. The value for organic soil is approx. 50 c_{uk} and for silty clays approx. 100 c_{uk}. Columns with other binders can be stiffer and for these E_k is put equal to 50-150 c_{uk}.

For mass stabilisation applications, M_k, the characteristic value of compression modulus (constrained modulus with confined compression) is put equal to 50-100 c_{uk}. The value for organic soil is approx. 50 c_{uk} and for silty clays approx. 100 c_{uk}. Stabilisations with other binders can be stiffer and for these M_k is put equal to 50-150 c_{uk}.
As stated earlier it is essential to make a prognosis of the magnitude and rate of settlement during the preloading time. Today the columns are usually considered as drains because the permeability of columns is higher than that of the original soil. In an engineering approach the theory also takes into account the increase of strength in columns with time and loading. For the calculation of the rate of settlement, the permeability of lime stabilised organic soil may be assumed to be approx. 1000 times as high as that of unstabilised clay. In the calculation the permeability of soil stabilised with other binders (e.g. lime/cement) can be assumed to be 200-600 times as high as that of unstabilised soil. The permeability of stabilised soil is difficult to estimate in advance and therefore results from calculations of rate of settlements must not be given as exact values but in an interval.

4.7 Design values

4.7.1 General

The partial factors applied to the characteristic value for ULS depend on the particular design condition. The partial factors applied for the final structure should be in accordance with the boxed values given in Eurocode 7 or national regulations or determined on the basis of special investigation and stated in the construction specifications. Lower partial factors, as recommended below, may be used for some temporary design situations.

4.7.2 Unit weight of stabilised soil

Design values are equal to characteristic values set out in 4.6.

4.7.3 Strength and deformation properties of soil

Parameters of unstabilised soil are given in 5.
In calculating the ultimate limit state, the value of γ_m for strength parameters is taken from Eurocode 7 or national regulations.
In calculating the serviceability limit states, settlements are calculated with characteristic values in accordance with Eurocode 7 or national regulations. Total and differential settlements are then corrected with respect to the uncertainty of calculated values. It must be noted here that column stabilisation and mass stabilisation is often combined with preloading and that the main part or all of the settlement therefore occurs during the construction period.
Design values should primarily be based on field tests. Design values based on laboratory mixed samples shall consider the difference between laboratory and field strength.
Note that in the calculation model presented below no consideration is given to the fact that the maximum undrained shear strength is not mobilised at the existing low strain levels in column stabilisation.

4.7.4 Laboratory tests

Mixing trials are performed for characteristic soil strata. To provide a basis for the determination of the quantity of binder required in stabilisation, several mixes are normally tested in the laboratory.
Laboratory tests, field test and parameters of stabilised soil are given in 6.

4.8 Design

4.8.1 General conditions

Calculation methods, which have been found reliable for non-organic soils and for organic soils in the EC-project ”EuroSoilStab”, are set out below with the modifications known at present. Road and railway embankments are subject to the requirements in Eurocode 7 or national regulations.
Calculation models presented in this publication assume interaction between column and unstabilised soil, see 4.2.3. With regard to limitation of the characteristic value of undrained shear strength c_{uk}, see 4.2.3.
Stabilised soil columns are inhomogeneous to varying degrees, with an irregular structure and properties varying in different directions. The columns are primarily intended to interact with soil when the columns are loaded axially. For other load situations, the shear strength of the columns may be lower than under axial loading. Columns subjected to tensile stresses shall be avoided.
Low values are recommended for β and c'_k (see 4.8.2). The reason is that the whole ultimate value is not mobilised.

4.8.2 Design in the ultimate limit state

Initial choice of type of geotechnical structure – calculation with characteristic values
When choosing the geotechnical structure the safety factor is calculated for characteristic values. The safety factor for the construction on unstabilised soil (i.e. the construction but without columns) shall be higher than 1.0. In some cases this means that temporary loading berms are needed.
If the factor of safety with respect to failure of an unstabilised embankment (including loading berms if any) is higher than 1.0, the columns may be placed in a square or rectangular pattern.
When the factor of safety with respect to failure (unstabilised embankment) is lower than 1.0 and there is no space for loading berms, columns in the shear zone shall be placed in panels or grids.
In stability calculations, the assumed shear strength of the columns should be limited to
100 kPa (lower values can of course apply when tests on columns in the field or laboratory mixed specimens give lower values). Under favourable conditions, shear strengths up to 150 kPa may be used at greater depths, e.g. under fill, with a factor of safety $F > 1.2$ for unstabilised soil (i.e. the same construction but without columns).
Stabilisation in the passive zone of slip surfaces should be avoided unless it is made in the form of panels or blocks. The soil strata outside the stabilised volume shall also have adequate bearing capacity to carry the loads transmitted to the unstabilised soil by column stabilisation.

The slope of the ground surface influences the design of stabilisation. If the slope of the ground surface is steeper than 1:7 and the factor of safety for the unstabilised embankment is lower than 1.2, the columns shall be placed in panels.
Stabilisation in the shear zone shall be designed in the form of panels.

Design

According to EC1 the uncertainties in the calculation model can be accounted for by using γ_{Rd}. No practice has been established on how to choose γ_{Rd} when dealing with column or mass stabilisation. In the equations suggested below γ_{Rd} =1.0. Further research is needed to derive a suitable value especially when stabilisation is made in organic soils.
Design shall be performed by combined analysis and by undrained analyses. Combined analysis means that the lowest value of τ_{fd} or τ_{fu} is selected for each section of the slip surface. When assessing pore pressures the original pore pressure conditions shall be regarded as well as the influence from column installation and loading. The approach described below assumes that stabiliser is present over the entire cross section of the columns, and that the columns are homogeneous.

The following values are recommended in stabilised columns in clay and organic clay (if no laboratory values are available):

$$c'_{k(col)} = \beta\, c_{ukcol} \tag{4.1}$$

$$\phi'_{k(col)} = 30^{o} \tag{4.2}$$

The value of β ranges from 0 to 0.3; it is put at 0 in the passive zone, to 0.1 in the direct shear zone and to 0.3 in the active zone.
For columns of stabilised gyttja or stabilised peat experience is lacking but normally $c'_{k(col)}$ and $\phi'_{k(col)}$ is chosen as for non-organic soil as given in equations 4.1 and 4.2. The values of $c'_{k(col)}$ and $\phi'_{k(col)}$ can also be judged from laboratory investigations, Cf. Chapter 6.
In the same way as in undrained analysis, c' for the column stabilised volume is calculated in accordance with Equation (4.3). The characteristic drained shear strength τ_{fdk} is calculated in accordance with Equation (4.4). If it is assumed that $\phi'_{k(col)} = \phi'_{k(soil)} = 30^{o}$, ϕ'_k can be put at 30^{o}.

$$c'_k = a\, c'_{k(col)} + (1-a)\, c'_{k(soil)} \tag{4.3}$$

$$\tau_{fdk} = c'_k + \sigma' \tan \phi'_k \tag{4.4}$$

where:
$a = A/c^2$, for rectangular column pattern
A = area of cross section of columns
c = distance between column centres

Undrained parameters are obtained from Equations (4.5) and (4.6).

$$c_{uk} = a\, c_{uk(col)} + (1-a)\, c_{uk(soil)} \tag{4.5}$$

$$\tau_{fuk} = c_{uk} \tag{4.6}$$

The above principle of calculating the stability of embankments on stabilised soil is based on full interaction between columns and soil. When soils in which creep deformations are in progress are stabilised, full interaction between columns and unstabilised clay cannot be relied on.

Column stabilisation for embankments

Present experience of column stabilisation in soft organic soil is limited. Embankments higher than 2 m normally presuppose the use of loading berms. Note that the safety factor for the construction on unstabilised soil (i.e. the construction but without columns) shall be higher than 1.0, see previous section “Initial choice of type of geotechnical structure – calculation with characteristic values”.
The bearing capacity of the stabilised soil during different stages of construction shall be determined by slip surface calculations. Installation of columns has the temporary effect of reducing the bearing capacity of soil during the construction stage. This should be taken into account. Loading on stabilised

soil results in high pore pressures in soil and columns. In construction specifications recommendations are given for load application sequence, possible restrictions on excavation and restrictions on future land use in the vicinity of the stabilisation.

The following check calculations shall always be performed. Further checks may be necessary depending on the purpose of stabilisation, design etc.:
- The factor of safety for the planned embankment without column stabilisation.
- The factor of safety after column installation during load application, with checks on maximum permissible load increments/level differences and slope gradient. Check on working sequence.
- The factor of safety for the column stabilised embankment during the construction stage with temporary surcharge, limitations concerning temporary storage sites, construction traffic etc.
- Factor of safety during the serviceability stage for the completed embankment with traffic load.

The columns are made so long that the slip surfaces, which pass below the stabilisation, have a satisfactory factor of safety. The slip surfaces, which pass substantially through the stabilisation, shall have at least the same factor of safety. This presupposes that the strength of unstabilised soil and column is mobilised simultaneously and that the columns act as a rigid body together with the soil. In such cases slip surface calculations can be based on a weighed shear strength in the active part of the slip surface, in accordance with Equation (4.3) and (4.5).

During installation of columns, mixing in some zones may be substandard and strength may therefore be lower. In those cases it is essential to impose the following limitations in design:
- a disturbed zone in the unstabilised soil below each column;
- reduced strength over the top metre length of the column.

The extent of the disturbed zone below the columns depends on the design of the mixing tool and the column diameter. For columns of 0.5-0.6 m diameter, a disturbed zone of approx.
0.5 m in length is normally obtained below the column. In the disturbed zone reconsolidation will occur in the long term.
Pressure feed of binder shall normally be stopped 0.5-1.0 m below ground level to prevent the binder being blown back along the shaft. This means that the top metre of the column may have varying properties. The strength in this section may be lower than that of the original dry crust.
Stability calculations are performed with a weighted value of shear strength, see Equation (4.3) and (4.5).
If the factor of safety with respect to failure of an unstabilised embankment (including loading berms if any) is sufficient, the columns may be placed in a square or rectangular pattern. See previous section " Initial choice of type of geotechnical structure – calculation with characteristic values".

<u>Columns in panels/grids or blocks</u>
When the factor of safety with respect to failure (unstabilised embankment) is too low and there is no space for loading berms, columns in the shear zone must be placed in panels or grids. The object of placing columns in panels, grids or blocks is to achieve better interaction between the columns and the soil. The distance between the panels is adjusted so as to achieve interaction between the panels and the soil, and to prevent uneven settlement in the superstructure.

<u>Mass stabilisation</u>
In stability calculation the mass stabilisation is assumed to be a homogeneous block.

4.8.3 Design in the serviceability limit states

<u>Calculation model, general</u>
Deep stabilisation should be combined with preloading by temporary surcharging. The purpose of surcharge is to consolidate the soil for a load higher than the service load. Removal of part of the surcharge load at the end of the preloading period reduces future creep settlements.
Requirements in the serviceability limit states are specified by the client; see 4.1. Note that the requirements in e.g. the codes refer to settlements during the service life of the road. It is thus possible to develop large settlements during the preloading stage and as a consequence derive very small settlements during the service stage.

The load on an area stabilised with columns is carried partly by the columns and partly by the unstabilised soil between the columns. The compression modulus of the columns is considerably

higher than that of the unstabilised soil. Settlements under load will therefore be significantly smaller on a stabilised surface than on an unstabilised surface.
The calculation model presented below has its origin in the model for lime columns described by Broms (1984). The model has also been used for soft and semi-hard lime cement columns, see Rogbeck et al (1995).

Settlements within the stabilised soil volume are influenced by the following factors:
- the ratio of the compression modulus of the columns to that of unstabilised soil;
- the proportion of the stabilised surface occupied by columns;
- the consolidation properties of the soil;
- the bearing capacity of the columns;
- the time of load application in relation to column installation;
- the permeability in unstabilised soil and in the columns.

The calculation model assumes that the depth of soil is uniform and that all columns penetrate to the same depth. Since there is a variation in the properties of unstabilised soil and in the effect of binder stabilisation, it may be economical to use columns of different lengths. In such a case calculations regarding the magnitude of settlements must be made for different column lengths.

Distribution of load between columns and stabilised soil
Distribution of load between columns and unstabilised soil is calculated on the assumption that the same compression occurs in columns and unstabilised soil at every level. This implies that the load on the unstabilised soil is gradually transferred to the columns and that the load is transmitted to the bases of the columns, as shown schematically in fig 4.2. Settlements in the soil below the columns are calculated on the assumption that the load is transmitted to the bases of the columns. The permeability of the columns is higher than that of unstabilised soil, and the columns therefore speed up the consolidation process. This means that the stratum below the columns may be assumed to be drained by the columns.

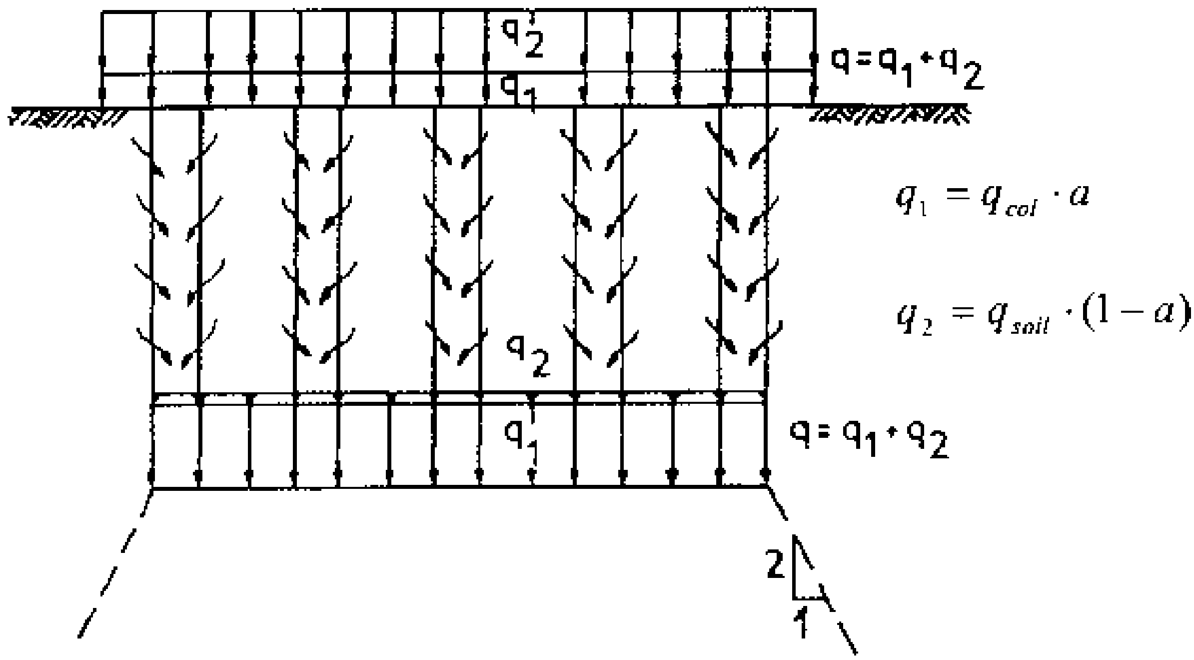


Figure 4.2. The principle of load distribution in column stabilisation.
The load q is made up of the load q_1 on the columns and the load q_2 on the unstabilised soil.

The compression modulus of columns increases in time. Due, inter alia, to different methods of mixing and stress ratios, the development of compression modulus is different in the field and the laboratory. The results of settlement calculations should therefore be given as probable maximum and minimum values.

Design of the preloading stage is based on characteristic values. By using the observational method, possible deviations from the predicted settlement can be found by settlement measurements during the construction phase. This will provide a basis for deciding when a temporary surcharge can be removed, whether the surcharge must be increased or the preloading period extended.
The load-deformation curve in stabilised columns may be assumed to conform to the curve in fig 4.3. The curve is linear up to the long-term strength (creep strength) of the columns, and the slope of the curve represents Young's moduli of the columns, E_{col}. Once the long-term strength has been exceeded, load on the columns is assumed to be constant. The load-deformation relationships described are used to calculate the distribution of load between the columns and unstabilised soil.

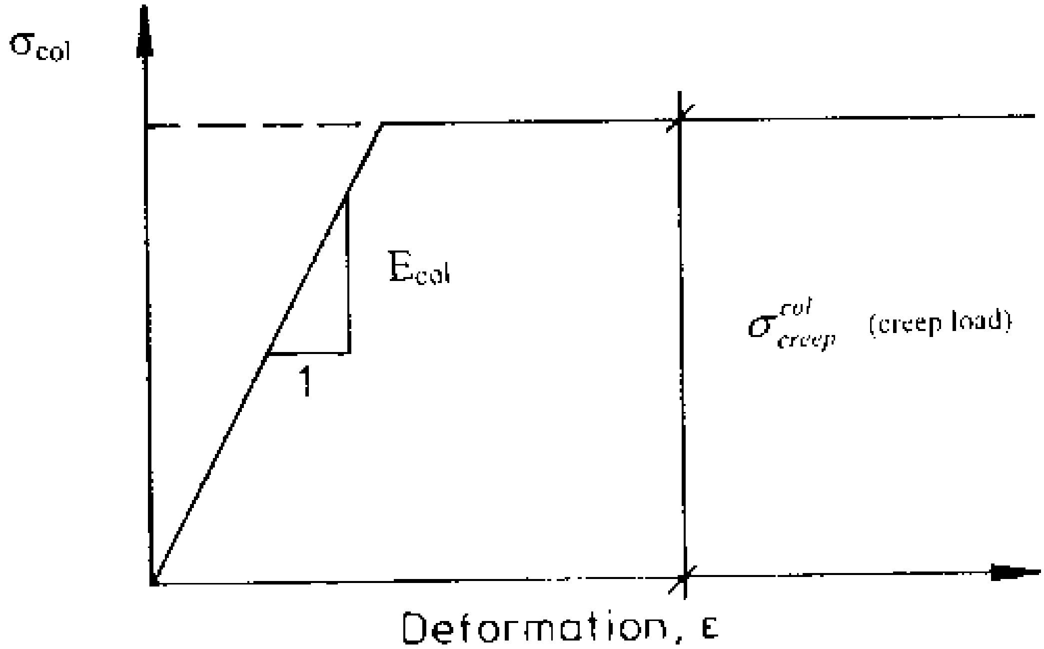


Figure 4.3. Assumed load-deformation curve in column of stabilised soil.

The ultimate strength σ_{ult} is a function of the shear strength c_{uk} of the columns and the effective horizontal pressure σ'_h on the columns, according to the empirical expression:

$$\sigma_{ult} = 2\,c_{uk} + 3\,\sigma'_h \qquad (4.7)$$

σ´h is the horizontal effective stress between the soil and the columns. It can be put equal to the original effective vertical pressure in the soil due to the deformations, which occur when the stabiliser is mixed in. Equation (4.7) is to some extent based on total stress analysis with $\phi = 30^o$ in the column.

Distribution of load between columns and unstabilised soil is calculated by an iteration process. Normally account is also taken of the fact that the horizontal pressure increases when a load is imposed on the area stabilised by columns. The increase in horizontal pressure is assumed to be 50% of the imposed load on the soil, according to Equation (4.8), and this means that the creep load of the column increases and the column thus takes a larger load.

$$\sigma'_h = \sigma'_{v0} + 0.5 \cdot \Delta\sigma_v \qquad (4.8)$$

The long-term strength of stabilised columns, σ_{creep}, can be put at 70-95% of the ultimate strength.
If the long-term strength of the column is 90% of its ultimate strength, this means that the individual column is designed to carry the maximum load q_{1max}.

$$q_{1max} = 0.90 \cdot a \cdot \sigma_{ult} \qquad (4.9)$$

where:
a = A/c^2, for rectangular column pattern
A = area of cross section of columns
c = distance between column centres

The creep load varies with the distance below ground level. The load q_1 carried by the individual column is at all times less than the total load q. The load q_2 on the unstabilised soil is calculated as the difference between the total load q and the load q_1 carried by the columns.

$$q_2 = q - q_1 \qquad (4.10)$$

Calculation of settlements

Settlements within the area stabilised by columns are calculated by dividing the soil profile into characteristic strata. Settlement in the columns is calculated in accordance with Equation (4.10) where Δ_h is the stratum thickness.

$$S_1 = \Sigma \frac{\Delta h}{a} \cdot \frac{q_1}{E_{col}} \qquad (4.11)$$

where:

S_1	= settlement in the column, m
Δ_h	= stratum thickness, m
$q_{1/a}$	= load on column as above, kPa
a	= ratio of areas as above
E_{col}	= Young's modulus of column, kPa

Settlement in the unstabilised soil is calculated in accordance with Equation (4.12)

$$S_2 = \Sigma \frac{\Delta h}{1-a} \cdot \frac{q_2}{M_{soil}} \qquad (4.12)$$

where:

S_2	= settlement in unstabilised soil, m
$q_{2/(1-a})$	= load on unstabilised soil as above, kPa
M_{soil}	= compression modulus of unstabilised soil, kPa

A first calculation is made by assuming that $q_1 = q_{1max}$. The calculated settlement S_1 in the columns is compared with the calculated settlement S_2 in the unstabilised soil. If $S_1 > S_2$, a load transfer is performed by gradually reducing q_1 and correspondingly increasing q_2, so that finally $S_1 = S_2$. The calculated settlement S_m is then equal to S_1 and S_2.
If the soil is normally consolidated, S_m can be calculated from Equation (4.13).

$$S_m = S_1 = S_2 = \Sigma \frac{\Delta h \cdot q}{a \cdot E_{col} + (1-a) \cdot M_{soil}} \qquad (4.13)$$

If however $S_1 < S_2$, the columns cannot take any more load, and the settlement S_m which occurs is equal to the calculated settlement S_2 in the unstabilised soil.
Settlements within the mass stabilised area are calculated by assuming the mass stabilised volume to behave as a linear elastic perfectly plastic layer. All of the load q is carried by the mass stabilised volume. The strength must be chosen at such an extent that the yield strength of the stabilised soil is not exceeded. The settlement is calculated in accordance with Equation (4.14). Note that considerable settlements can be derived during the curing period (when the load only consists of the working platform) and these settlements have to be calculated separately.

$$S_m = \Sigma \Delta h \cdot \frac{q}{M_m} \qquad (4.14)$$

where:

S_m	= settlement in the mass stabilised volume, m
Δh	= stratum thickness, m
q	= load on mass stabilisation, kPa
M_m	= compression modulus of mass stabilised soil, kPa

When using mass stabilisation a preloading working platform should be applied soon after the stabilisation work. This compresses the stabilised volume and increases its strength. The amount of settlement is much depending on the soil to be stabilised. For peat and dredging mud quite a large settlement can occur due to the compression (compression could be up to 30-35 %). In the laboratory procedure suggested for preparation and storing of test samples for Mass Stabilisation Applications it is suggested that the compression of the test sample should be measured in the laboratory. These recordings can be used for calculation of the immediate settlements. However, these settlement develops rapidly. The settlements of the mass stabilised layer in the service time are usually small.
If columns are made beneath mass stabilisation the settlement calculation for the columns stabilised volume is carried out as previously explained.
Calculation of settlement as above holds only for the stabilised volume. Calculation of settlement in strata below the stabilised volume is carried out in the traditional way. No spread of load is assumed to occur in the stabilised volume.

Rate of settlement
When the effective stress in the soil is less than the preconsolidation pressure, settlements will develop rapidly.
When the effective stress in the soil exceeds the preconsolidation pressure, the rate of consolidation settlement in the stabilised soil stratum is calculated in the same way as for vertically drained soil. Experience shows that the permeability of the macrostructure of the column is 200-600 times higher than of unstabilised soil.

As stated earlier it is essential to make a prognosis of the magnitude and rate of settlement during the preloading time. Today the columns are casually considered as drains and the theory does not take into account the increase of strength in column with time and loading. For calculation of the rate of settlement, the permeability of lime stabilised organic soil may be assumed to be approx. 1000 times as high as that of unstabilised clay. The permeability of soil stabilised with other binders (e.g. lime/cement) can in the calculation be assumed to be 200-600 times as high as that of unstabilised soil. The permeability of stabilised soil is difficult to estimate in advance and therefore results from calculation of rate of settlements shall not be given as exact values but in an interval.
For fill on top of lime and lime cement columns with the columns spaced at 0.8 - 1.8 m between centres, the rate of settlement can be approximately calculated from an equation for radial flow (originally from Barron, (1948), and modified as presented in Åhnberg et al, (1986); see also Hansbo, (1979)).

Note that calculation of the rate of settlement is only approximate. Monitoring shows that the calculated rate of settlement is broadly correct when 80-90% of the total settlement has developed.

$$U = 1 - \exp\left[\frac{-2 \cdot c_{vh} \cdot t}{R^2 \cdot f(n)}\right] \qquad (4.15)$$

where:

U	=	degree of consolidation
c_{vh}	=	coefficient of consolidation in unstabilised soil in the horizontal direction and for vertical deformation normally assumed to be equal to 2 c_{vv}
c_{vv}	=	coefficient of consolidation in unstabilised soil in the vertical direction and for vertical deformation
t	=	period of consolidation
R	=	influence radius of columns

For columns installed at distances c between centres in a square grid or one made up of isosceles triangles, the influence radius is R = c/(π)1/2 = 0.56c. If the columns are placed in a grid of equilateral triangles, R = 0.53c.

$$f(n) = \frac{n^2}{n^2-1} \cdot \left[\ln(n) - 0.75 + \frac{1}{n^2} \cdot \left(1 - \frac{1}{4 \cdot n^2}\right)\right] + \left[\frac{n^2-1}{n^2} \cdot \frac{1}{r^2} \cdot \frac{k_{soil}}{k_{col}} \cdot L_D{}^2\right] \qquad (4.16)$$

where n=R/r:

r	=	column radius
c	=	distance between column centres
L_D	=	column length with drainage upwards only and half column length with drainage both upwards and downwards
k_{soil}	=	permeability of unstabilised soil
k_{col}	=	permeability of columns

The rate of settlement as above holds only for the stabilised volume. Calculation of the rate of settlement below the stabilised volume is performed in the traditional way, bearing in mind that the columns drain into the top of the stratum.

5. Properties of unstabilised soil

5.1 Introduction

Because of the use of the local subsoil as a constructive part of the deep stabilisation method, the technique of stabilised soil columns requires a very good quality of the site investigation. Therefore it is very important to pay special attention to the site investigation.

When the location of the construction site is known, the site investigation can be performed. In general, the site investigation will take place before the design process of the project is started. It is important to know the characteristics of the subsoil to be able to make a proper decision on the exact location of the project, and to make a design of good quality. If necessary, the site investigation can be done in two phases: first, a preliminary investigation and after that a more detailed, final site investigation. The preliminary investigation can be done using CPT-tests and other borings to get sufficient information for a preliminary design. The levels of the layer boundaries and the types of subsoils are known at that stage. The preliminary design can be used for a first approximation of the costs of the project, and to get an idea of the technical difficulties of the project. In the second phase, the final design will be based on the detailed site investigation which is needed to make a design of good quality with stabilised soil columns and/or mass stabilisation.

So the main aim of the site investigation is identification and description of the characteristic soil layers. A secondary aim is that the presence of obstacles in the subsoil is investigated.
In the upcoming paragraph the site investigation will be described in more detail.

5.2 Characteristics of the site

The site investigation can be divided in two categories:
- insitu testing
- laboratory testing

In general, standard test equipment is used. No results of special devices are needed for the application of stabilised soil columns in the design process. The tests which are described in this paragraph are especially suitable for soils with a high organic content. When fibrous peats are expected special attention should be paid to the reliability of the test results in relation to the determination of the parameters needed for the design process.

The in-situ tests are being executed by using for example CPTu's (CPT with pore pressure measurement) and boreholes for determination of the geotechnical profile and taking samples for laboratory testing to identify and describe characteristic soil layers. For a description of the methods and equipments the latest report from TC 16 is recommended (draft or final). In case of heterogeneity in the subsoils, special attention should be paid to the determination of the layer boundaries and their variations. For the CPTu tests a minimum of 3 tests with a maximum distance of 40 meter is required. In general, extra CPT's and borings are recommended.
Pore pressure measurements are necessary to determine the hydrological situation.
In the Eurocode 7 part 3, a general description of these techniques is given.

Disturbed and undisturbed samples are necessary to obtain material for the laboratory testing. Undisturbed samples in organic clays are preferably taken by piston sampling or the "Delft sampler". For peaty soils a peat sampler is being used, e.g. the peat sampler of the Swedish Geotechnical Institute.

For determination of the in-situ undrained shear strength CPT test results or vane tests are used. The undrained shear strength will be needed for a stability analysis. The tests are minimally performed each 50 metres.

The level of the ground surface should be measured relative to a reference coordinate system. This measurement is used as a reference.
The laboratory tests can be divided in tests for classification, engineering properties, chemical properties and environmental properties.

a) The classification tests are performed to obtain knowledge on the type and consistency of the subsoil. The tests should be performed for each individual soil layer. In these tests the following parameters are determined:

- liquid limit
- plastic limit
- plasticity index
- organic content
- water content
- density
- sensitivity
- Von Post (for peat classification)
- grain size distribution
- clay content

The tests are being performed using standard geotechnical tests as described in ETC 5 and Eurocode 7. The results give the engineer an idea of the suitability of the soil layers for deep stabilisation and/or mass stabilisation.

b) The most important engineering properties are the undrained shear strength, the compressiblity and the permeability. The shear strength properties are determined by e.g. unconfined compression tests, triaxial tests or the fall-cone test according to ETC 5. In case of a high organic material the undrained shear strength is rather high. Another method is to use the CPT-results. A good estimation is that the undrained shear strength is 5 - 10% (depending on the type of soil) of the cone resistance q_c of a particular soil layer. In case of soils with high organic content this method is recommended. The determination of the undrained shear strength for example gives an idea of the suitableness of stabilising the soil.

The deformation properties compressibility and permeability are determined using oedometer tests (incremental loading or Constant Rate of Strain) according to ETC 5. The tests should be executed with loading, -unloading and reloading stress paths.

The permeability can be determined using falling head tests, constant head tests or oedometer tests (incremental loading or CRS). These tests are also described in detail in ETC 5 and performed in the laboratory. The permeability can be determined in situ by performing the same type of tests or a rising head test in a standpipe. In this test the water in a standpipe is lowered. An estimation of the permeability can be made using the time needed for the groundwater to fill the standpipe again.

The engineering properties of the original soil are used in the design. They can also be used as a reference for the results of the stabilised soil. This gives the engineer an impression of the improvement of the soil.
For the determination of a representative set of engineering properties, tests should be performed in each individual soil layer.

c) The chemical properties should be established to give empirical guidelines and to support the choice of the amount and type of binder. The following parameters are determined:
- sulphate content
- chloride content
- carbonate content
- humid acids/TOC
- cation exchange capacity (according to ISO 13536 or 11260)
- pH of the groundwater

These tests are also being described in the Eurocode.

d) To determine the environmental impact of the stabilisation, tests should be carried out. The environmental properties are:
- pH (according to ISO 10390)
- cation exchange capacity (according to ISO 13536 or 11260)
- sulphide content
- carbonate content
- type and total concentration of ion and metals. These tests are used as a reference measurement.
- available concentration of ion and metals from leaching tests.

6. Properties of Stabilised Soils

6.1 Introduction

Successful and cost effective application of deep stabilised soil (columns and mass stabilization) requires a combination of laboratory and field tests in order to assess the engineering and environmental properties. Local experience should be considered, e.g. influencing the magnitude of testing.

In the first stage of the project laboratory testing including mixing soil and binder and testing the stabilised soil in the laboratory should be performed to judge the effects of deep stabilisation for the actual soil(s). The most important results from the laboratory tests are enhanced knowledge of suitable types and amounts of binders.

In the second step the engineering and environmental properties are determined in situ which is done by installing and testing an appropriate number of trial columns (pads of mass stabilisation). Based on these test results the type of binder, amount of binder, installation method etc. and the design values for the final design are chosen.
It is important to identify all soil layers and pay attention to layers requiring special measures regarding e.g. binders and mixing technique.

6.2 General properties of stabilised soil

Properties of stabilised clay, gyttja and peat mainly depend on the type of binder used for stabilisation, its quantity and the geotechnical and chemical properties of the soil itself. The properties significantly change with time, e.g. increase in strength with time after mixing. The properties of a stabilised soil cannot be forecasted reliably on the basis of the properties of the natural soil to be stabilised. In every case it is necessary to conduct laboratory and field investigations on stabilised soil.

Mass stabilisation is a stabilisation of the entire soil volume. With column stabilisation there will remain natural, not stabilised soil between the stabilised columns. However, the columns reinforce the soil around them like steel reinforcements in concrete. Therefore, interaction between the columns and the surrounding soil is very important. An example of this is shown in figure 6.1 where the migration of lime-based binders can be seen as a greyish area around the columns that were stabilised with a mixture of lime and gypsum.

Figure 6.1. Migration of lime from a column to the surrounding soil.

6.2.1 Stabilised soil - investigations in the laboratory

The laboratory investigations on stabilisation should be made in a certain order to obtain reliable and optimal results:

1. Firstly, vertically continuous / almost continuous samples are taken from the most crucial and difficult points (for example the deepest deposits of soft soil) of the site to be stabilised. The sampling points are chosen on the basis of the basic geotechnical data. The soil samples are tested regarding their geotechnical and chemical characteristics (Ch. 5). The results will show the

variance in soil stratigraphy and guide the choice of soil layers, potential binder types and binder quantities for the stabilisation tests.

2. The first stabilisation tests are made in order to screen out the binder alternatives and to choose the optimal one. The screening tests involve unconfined compression strength tests on test pieces that have been stabilised for 28 or (recommended) 90 days.
3. Finally, the optimal binder quantity and the stabilisation effect with time will be investigated (by unconfined compression strength tests). When necessary the more precise design parameters will be determined with triaxial test.

In the Table 6.1 there are given examples of the relative strength increase based on laboratory tests on Nordic soils with different binder mixes in different types of soil.

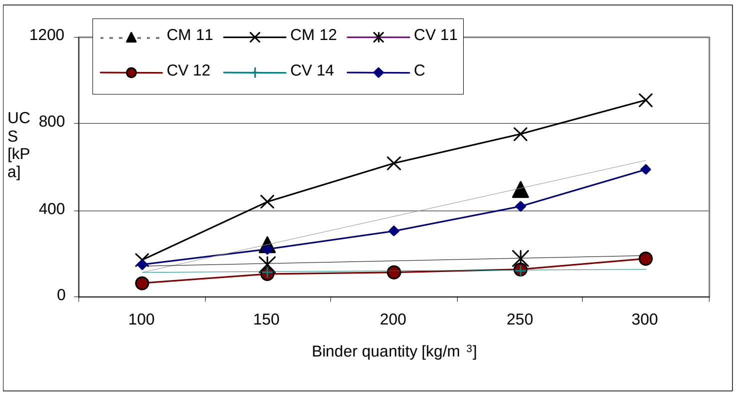
Table 6.1. Relative strength increase based on laboratory tests (unconfined compressive strength after 28 days of curing) on Nordic soils.

Binder	Silt Organic content 0-2%	Clay Organic content 0-2%	Organic Soils, e.g. Gyttja Organic Clay Organic content 2-30%	Peat Organic content 50-100%
Cement	xx	x	x	xx
Cement + gypsum	x	x	xx	xx
Cement + furnace slag	xx	xx	xx	xxx
Lime + cement	xx	xx	x	-
Lime + gypsum	xx	xx	xx	-
Lime + slag	x	x	x	-
Lime + gypsum + slag	xx	xx	xx	-
Lime+ gypsum + cement	xx	xx	xx	-
Lime	-	xx	-	-

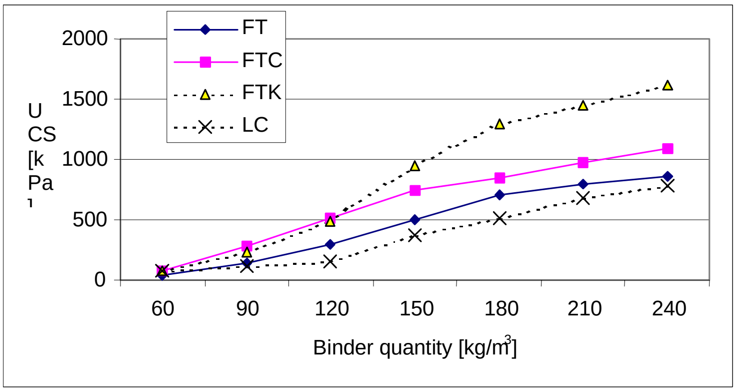
xxx very good binder in many cases
xx good in many cases
x good in some cases
- not suitable

6.2.2 *Effect of binder quantity (laboratory tests)*

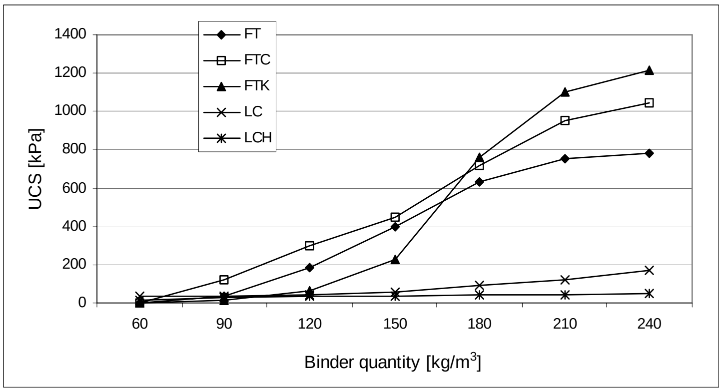
The effect of binder quantity on the strength of the stabilised soil was tested in the laboratory in the EuroSoilStab –project. In figure 6.2 a few examples are given. It is evident that the effect of quantity differs between the different binders. For example the quantity of furnace slag significantly affects the stabilisation of peat.



a.



b.



c.

Figure 6.2. EuroSoilStab examples on the effect of binder quantity on strength (unconfined compressive strength) 90 days after mixing.
a) peat from Söderhamn, Sweden;
b) clay from Kivikko, Finland;
c) gyttja from Porvoo, Finland.
Binder symbols: Numbers indicate the proportion of different binders that include: C = cement, M =blast furnace slag from Sweden, V = a Swedish fly ash, H = a Finnish fly ash, F = Finnstabi®-gypsum, T = a secondary hydrated lime with at least 50 % $Ca(OH)_2$, L = lime (CaO), K = blast furnace slag from Finland.

6.2.3 *Effect of the curing time (laboratory tests)*

The effect of curing time on different stabilised soils was investigated in the EuroSoilStab–project. It was evident that the effect of time differs between different mixes of binder and soil. When using only cement as binder the stabilisation reactions will almost totally be finished during the first month. On the other hand the stabilisation process of materials containing lime, furnace slag, gypsum or fly ash remarkably continues during several months thereafter. Therefore, there might be changes in the priority order of different binder mixes after 3-month tests when comparing the results with a choice after 1-month tests. Figure 6.3 gives a few examples:

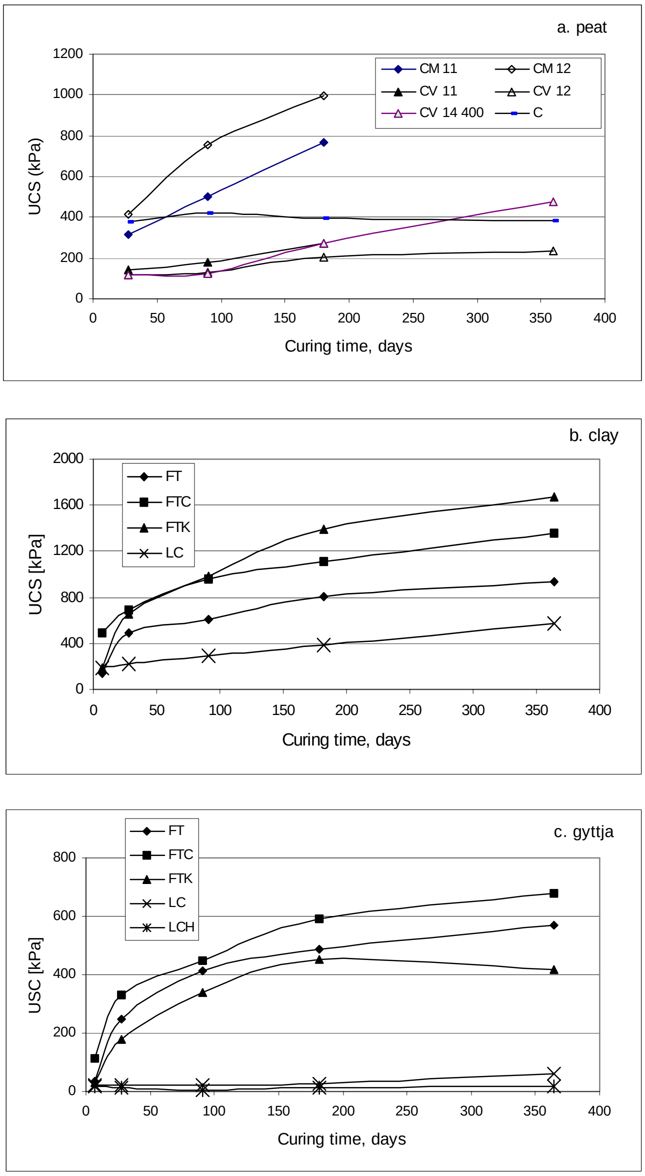


Figure 6.3. EuroSoilStab examples on the effect of curing time on;
a) peat of Söderhamn, Sweden;
b) clay of Kivikko, Finland;
c) gyttja of Porvoo, Finland.
For symbols, see text under figure 6.2.

6.2.4 *Effect on permeability (laboratory tests)*

Stabilisation will significantly affect the permeability of the soil. Binders based on lime or lime-cement mixes might increase the permeability in a clay with up to 100-1000 times. Permeability of that order in the stabilised soils is assumed in the design models (design system), but should not be used otherwise unless verified. When using gypsum and cement the materials generally become less permeable.

The time for stabilisation does not seem to affect the permeability to any large degree. For example, permeability tests on peat with different binders indicate that the permeability (k) of stabilised peat is between 10^{-9} … 10^{-8} m/s as well after 28 days as after 180 days.

6.2.5 Effect of preloading

Preloading of a mass stabilised area will significantly affect the stabilisation of peat. Therefore, the importance of this should be considered and the scheme of preloading should be planned accordingly. The possible preloading will be constrained by the stability of the embankment. Figure 6.4. gives examples of the effect of preloading on the basis of results in the EuroSoilStab-project.

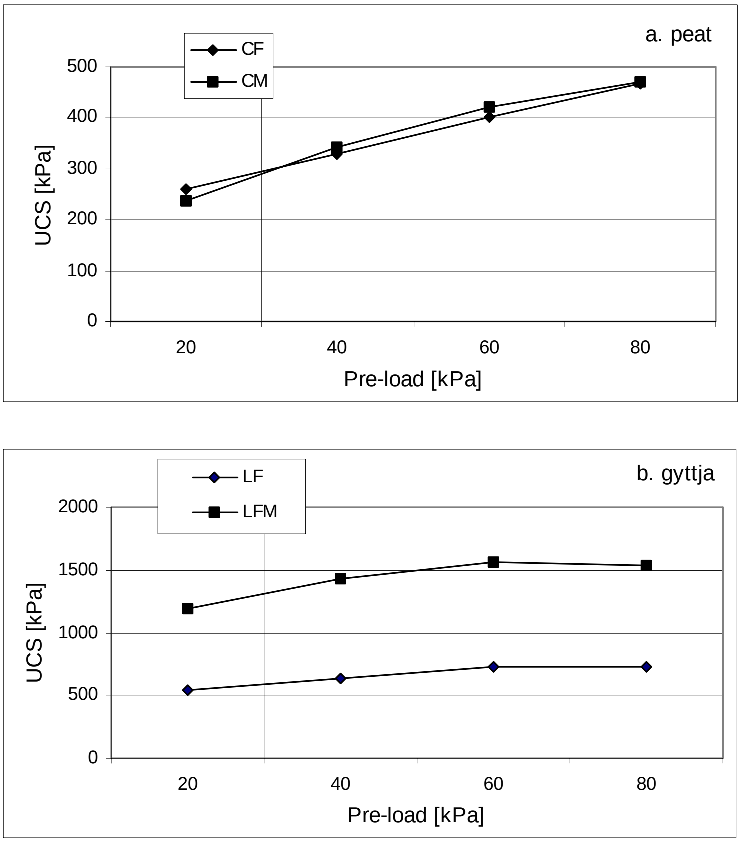


Figure 6.4. EuroSoilStab examples on the effect of preloading on.
a) stabilised peat from Kivikko, Finland.
b) stabilised gyttja from Porvoo, Finland.
Symbols, see in the text for figure 6.2.

6.2.6 Environmental acceptability

Leaching tests are chosen to determine the leaching behaviour and potential environmental harm of the stabilised soil when using different types of binders. Normally, leaching of stabilised clay and gyttja is tested by the diffusion test according to the Dutch standard NEN 7345. The column test (NEN 7343) is suitable to test leaching of stabilised peat.
In the EuroSoilStab-project the leaching tests were made on different stabilised soils and for comparison on natural soils as well. The stabilised soils were chosen to contain binders based on industrial by-products like fly ashes, furnace slag and gypsum. The results indicate that there should be no increased risk on the environment by using binders based on lime and cement as well as the tested industrial by-products. The handling of test samples is described in 6.5.

6.2.7 Stabilisation in laboratory vs in the field

The strength of a laboratory-made stabilised test sample is usually significantly higher than the strength of a corresponding material from the field. The difference is mainly due to a more efficient mixing of the binder and soil in the laboratory. Also the prevailing temperature in a laboratory is more even and differs from the temperature in the field conditions.

The former is apparent when comparing the strength of well mixed laboratory test samples with the strength of samples from similar but less homogeneously mixed columns. In laboratory test samples the attainable strength is usually from 10 to 50 times higher than the strength of the natural (not stabilised) soil. In column stabilisation the attainable strength is normally from 20 % to 50 % of the strength of the laboratory test pieces.

$$\tau_{fu\ (stab\ soil)} = 10 \ldots 50 * \tau_{fu\ (soil)}$$

$$\tau_{fu\ (col)} = 0{,}2 \ldots 0{,}5 * \tau_{fu\ (lab)}$$

where

$\tau_{fu\ (stab\ soil)}$	=	Undrained shear strength of stabilised laboratory test samples
$\tau_{fu\ (soil)}$	=	Undrained shear strength of natural soil
$\tau_{fu\ (col)}$	=	Undrained shear strength of stabilised columns

The correlation between laboratory test specimen and field samples is usually better at lower strength levels and as the lime content of binder is increasing. In mass stabilisation the mixing in situ might give about the same strength in the field as that of laboratory test specimen.

6.3 Binders

6.3.1 Type of binders

Binders may be hydraulic, that is self setting in contact with water or they may be non-hydraulic, that is they need some material to react with in order to set. Non-hydraulic binders may be used to activate latent hydraulic materials to produce reactive blended products. A hydraulic binder will stabilise almost any soil but in order not to produce a heterogeneous end product the mechanical mixing of the binder into the soil must be very good. Non-hydraulic binders generally react with clay minerals in the soil, which will result in a stabilised material with improved geotechnical properties.

When appropriate, quality of binders should be defined according to existing CEN standard.

<u>Lime</u>

Lime is available in two forms. Either as quick lime (CaO) or hydrated lime ($Ca(OH)_2$).
Hydraulic lime is also available but experience of suitability for deep stabilisation is limited.
Lime stabilisation is based on a reaction with minerals in soil or with added mineral materials. Reaction products are calcium-silicate-hydrate, CSH and calcium-aluminum-silicate-hydrate, CASH. Quick lime will react with the water in the soil and form hydrated lime. In addition to chemical binding of water this reaction also releases heat which will contribute to faster reactions and a reduction of water content.

$CaO + H_2O \Rightarrow Ca(OH)_2$ + heat

- hydration of lime, drying out soil
- ion exchange reactions, effect on soil structure
- increase of pH value, increased solubility of Si and Al from mineral matter
- pozzolanic reactions, long term stabilisation reactions

Reference standard: CEN standard EN 459-1. CL 80 and CL 90 are examples of quick limes.

Cement

Cement is a hydraulic binder. Setting of cement will enclose soil as a glue but it will not change the structure of clay soil to the same extent as lime does. Some drying out of the soil also occurs. Cement is not dependent of a reaction with minerals but may stabilise more or less any soil material There are numerous different types of cement. Normally ordinary Portland cement is used for stabilisation purposes but this may vary between countries. A cement with finer grain size is more reactive. Different additives such as slag, ash or gypsum may be added to other types. CSH and $Ca(OH)_2$ is produced as reaction products of cement reacting with water.

Reference standard: EN 197. CEM I 42,5 and CEM II 42,5 are examples of labels of cement types that are used for stabilisation.

Blast furnace slag

Slag needs to be granulated to be reactive. It is cooled fast to get a glass structure, which is essential for the reactivity. This granulated product is grinded. The finer the grain size the more reactive the slag is. Blast furnace slag is activated with lime or cement to achieve a faster reaction. Chemically blast furnace slag is similar in composition to cement but the quality and reactivity varies between slags from different furnaces. Blast furnace slag may be regarded as a low cost substitute for cement. Normally blast furnace slag is used as part of a blended product.

Ash and FGD

Ash is a fine grained residue from a combustion process. FGD is the end product of flue gas desulphurisation. Composition of ashes varies depending on fuel and burning process. Most common fuels are coal, peat and biofuels. Flyash is collected from flue gases in some type of filter. PFA is used in U.K. for pulverized fly ash from coal combustion. Reactive components in ashes are SiO_2 and Al_2O_3. Nowadays many “plants” are equipped with some kind of desulphurisation unit. Limestone or lime is often used as a sorbent to capture sulphur from the flue gases. If flyash is mixed with FGD it may have reduced reactivity. FGD may be pure gypsum but it may also be calcium sulphate that is almost inert. This depends on the desulphurization technique that is used.

Pozzolanic reactivity of ash will vary within wide ranges and it should be determined for each product separately.

Ashes are as a rule not very reactive by them selves but may reduce the cost of a blended product.

Calciumsulphateproducts

Gypsum as a mineral raw material occurs in the dihydrate form, $CaSO_4 \bullet 2H_2O$. When heated to approximately 175 °C it looses some water and becomes hemihydrate, $CaSO_4 \bullet$ ½H2O. When calcined to a completely waterfree form it transforms to anhydrite, $CaSO_4$. Solubility of gypsum will produce Ca- and SO_4-ions, which activate for example blast furnace slag and flyash. In combination with soluble aluminates gypsum reacts to form ettringite. Calcium sulphate may be derived from a number of industrial processes as a secondary product.

Calcium sulphate products are used as components in blends.

Other secondary products

Kiln dust is an example of a secondary product from lime production. It is a fine grained material collected in a filter from the flue gases from the lime kiln. Mainly it contains calcium carbonate dust, fuel ash and some calcium oxide.

Silica fume is another example of a secondary product that may be used. It is a by-product of producing silicon metal or ferrosilicon alloy.

Such secondary materials are not standardised but manufacturers may have data sheets available. Technical performance for such products should be tested case by case to judge their suitability for stabilisation purposes.

Blends of dry binders
Above mentioned materials may be blended with each other in different proportions to optimize technical performance and economy with respect to the soil that will be treated. Blends may be factory produced or mixed at site by the stabilisation equipment.

Wet binders
For the wet method mostly cement is used as the binder. Prior to the stabilisation process the binder is mixed with water to achieve a slurry.

6.3.2 Requirements

Chemical composition	As described in existing standards mentioned above.
Flowability	Free flowing in machinery*
Grain size	Pneumatically transportable, must not block feeders
Recorded contents of blends	
Approved stabilisation tests in laboratory and in field	

Storage of binders
As most binders react with moisture they should be stored dry, in closed tanks. The precaution will also reduce dusting at the job site. Long storage time is not recommended for any binder because that could lead to decreased reactivity and flowability.

Safety aspects
Due to high alkalinity most materials are irritant for eyes and skin. Inhalation should be avoided. In reaction with water or acids some binders develop heat.

These products should be handled wearing protective gloves, mask and goggles. Special attention should be given to handling where high pressure is involved for instance when unloading lorry tanks or when filling tanks on stabilisation equipment.

Consult safety data sheets for further details of each product.

Safety measures shall be in compliance with national legal requirements.

6.3.3 Choice of binder

For the choice of binder as function of soil types and requirements for example strength development in different soils see 6.2.

6.4 Laboratory tests

This section deals with the various laboratory tests that usually can be performed to gain information on matters as the best stabilizer to use at a given site, and the geomechanical properties of stabilised soil, notably strength, stiffness and compressibility, and permeability.

6.4.1 Test programme for mix design

The complexity of the chemical and physical interaction of organic clays, gyttjas and peats with stabilizer materials is such that it is not possible today to predict for a given site which stabilizer and dosage will yield optimal performance. Even rather similar soils or relatively slight variations of the properties of stabilizers may result in greatly different properties of the stabilised soil, and sometimes even small differences will contradict previous experience. A laboratory test programme to design an optimal stabilizer mix and dosage is therefore indispensable, and should be performed early in a project, the first step see 6.1.

Test procedures for preparing samples of soil stabilised by lime and cement-type materials for column stabilization and for mass stabilization and storing of these samples are given in 6.4.2 and 6.4.3 below. They describe in detail the steps to be taken to produce stabilised soil samples to be tested for

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* There is a national standard in Sweden for flowability of lime. SS 13 40 05. Lime products for industrial purposes – Determination of fluidness in lime products (in Swedish).
The method is also described in, von W. Imse; Mainz: Messung der Fließfähigkeit von Zement. Zement Kalk Gips N:o 3 1972.

strength, stiffness, compressibility and permeability by a variety of standard geotechnical tests. The soil to be used in preparing these samples should be representative of the soil layers at the site to be stabilised. Organic deposits are notoriously variable in both vertical and lateral directions, so that often a thorough site characterization will be needed to determine representative locations of soil samples.

The small sample size and the minimal loss of soil during the sample preparation procedure will limit the amount of soil to be collected, and usually standard sampling techniques will supply sufficient quantities of soil. The overall performance of a stabilised soil column will to a great extent be determined by its weakest part, and the mix design should take this into account by focussing on layers which are known to be difficult to stabilize. If such layers can be located with sufficient accuracy, it can be contemplated to specify more intensive mixing in them, as quite often this will produce better performance, so that the overall dosage of stabilizer can be reduced.

It is wise to test several stabilizers (each at several dosages) during the laboratory mix design programme. A general rule for the choice of stabilizer is difficult to give, but the evaluation of tests performed in EuroSoilStab context in Finland on soils and stabilizers specific to these countries, see 6.2 may give some useful guidelines.

Application of surface loading in the field before or shortly after stabilization can improve strength. Laboratory test programmes therefore sometimes include a load on the sample during its curing. This is especially the case for mass-stabilization of high water content peats as the top soil layer, see 6.4.3.

6.4.2 Laboratory procedure for test samples (column applications)

Scope

The preparation in the laboratory of samples of soil stabilised by mixing with lime and/or cement-type materials for deep mixing applications is specified. The focus is on soft cohesive soils, which may contain organic matter in varying degrees:, organic clay, gyttja or peat. Non-cohesive soil such as sand and silt may also be amenable to this test procedure. The stabilizer material may be lime or a cement (e.g. Portland cement or blast furnace slag cement) or a mixture of cement with additives such as ground granulated blast furnace slag, gypsum, lime, or fly ash. The samples serve for investigation of the properties of the stabilised soil, e.g. by means of the unconfined compression test or the triaxial test.

For mass stabilization applications, different procedures are necessary for the laboratory preparation of stabilised soil samples, see 6.4.3.

Significance and use

The present procedure is relatively simple and yields samples of stabilised soil suitable for the determination of strength and stiffness by means of laboratory strength tests on cylindrical samples such as the unconfined compression test, various kinds of triaxial test and direct shear tests. Other properties, such as permeability, physical and chemical durability, and compressibility may also be determined on such samples. The method yields samples, which may be used in determining type of stabilizer and dosage for deep mixing projects. The samples obtained by the method however do not reflect well the structure of soil stabilised in-situ by common deep mixing techniques. Conditions of mixing and curing in the laboratory deviate significantly from field conditions, and consequently laboratory strength and stiffness determined on samples prepared by this procedure will likewise deviate from field values. However, when planning a deep mixing project, a comparative laboratory investigation of the properties of different samples prepared with various stabilizer materials in varying dosages and after varying curing periods, is a useful, often indispensable aid. Further, empirical rules can be developed to allow for the differences in e.g. strength and stiffness between field-stabilised and laboratory-stabilised material. It is necessary to produce a number of trial columns ahead of or in the beginning of the actual project. Based on the results of the laboratory programme, a few stabilizer combinations and dosages can be applied, and the results are used to assist the final choice and to determine the engineering parameters for use in the final design.

More complicated procedures exist and are being developed which either mimic more closely the field deep mixing methods, and consequently reduce the empirical "laboratory/field" factor, or aim at improving the reproducibility of the sample properties (e.g. strength). Present indications are that the latter goal has not been reached, so that reproducibility of samples prepared by the present procedure is not necessarily improved by more complex methods.

The present procedure gives no guidelines as to the number of tests that should be performed, and the number of variables (e.g. different stabilizers, dosages, length of curing period, etc) that should be tested. These should be carefully planned when defining the laboratory investigation.

Materials and equipment

Soil
Soil is obtained from the site under investigation. It may be obtained by standard soil sampling devices such as tube and piston samplers and the continuous Delft sampler. Auger samples are acceptable if it can be shown that intermixing of different soil layers is kept within acceptable limits. Large diameter (>20 cm) augers have the advantage of allowing a large quantity of soil to be collected, while the soft soils in question are usually easily penetrated by them. However, large diameter tube samplers such as the SGI Peat Sampler may yield better samples in sufficient quantities and at comparable cost in most soft deposits.

Stabilizer
Stabilizers are materials with hydraulic properties such as Portland cement, blast furnace slag cement, ground granulated blast furnace slag, fly ash, slaked or unslaked lime, and gypsum (anhydrous, demi-hydrous or di-hydrous). The stabilizer used in the laboratory preparation of samples must be representative of the materials to be used in-situ, and must be adequately stored such that their properties are not impaired by exposure to moisture or moist air or extreme temperatures. If stabilizer material has been stored for long periods, its reactivity should be checked.

A stabilizer can be a mixture of two or more stabilizer materials. Filler materials such as sand, silica fume etc. can also be mixed in.

Some stabilizers, notably unslaked lime, have caustic properties, and proper safety precautions and procedures shall be adhered to in dealing with them.

Equipment
- Mixing machine of sufficient capacity to mix soil for the entire test programme (usually 20-50 liters).
- Mixing machine of sufficient capacity to mix a batch of soil with one binder (normally 3 - 5 liters).
- Cylindrical moulds, e.g. plastic tubes or plastic-coated cardboard, inner diameter 50 mm and length at least 100 mm. The ends must be flat and perpendicular to the length axis. The bottom of the mould may be closed by a flat and stiff lid, or placed on a flat plate. In both cases, the seal between mould and bottom should be tight enough to prevent loss of mixed soil. To allow minimum disturbance when removing the sample from the mould after curing the plastic moulds could e.g. have one lengthwise slit, allowing the mould to be pryed open during sample removal, or plastic or metal split moulds could be used. The slit or splits must be sufficiently clamped and be water-tight during sample placement and compaction. If cylindrical moulds without lengthwise slit are used the force used for removing of the sample from the tube should be minimised. If it is a problem to extract the sample from the mould a form oil based on wax can be used. If this form oil is used it shall be shown that it does not influence the properties of the sample.
- Fork: a kitchen fork the prongs of which may be bent at right angles over a length of approx. 15 mm.
- Compaction tool: a circular steel stamp, e.g. approx. 10 mm thick and with a diameter 5 mm less than that of the mould, with an attached steel rod e.g. approx. 50 mm long. Alternatively, a press capable of delivering a stress of 100 kPa on a stamp similar to that described above can be used. In sticky soils, it may be necessary to fit an inclined base to the stamp of such a press.

Preparation procedure

Homogenization of soil

> *Note* Details of the preparation method, such as type of mixing machine and mixing tool, power and r.p.m.'s of the mixing machine, duration of mixing etc. are not specified, but must be chosen on the basis of local experience with the soil and the available equipment. Classification of the soil in an early stage can assist the choices. Bulk unit weight, water content, organic content, degree of humification, particle size distribution and maximum fibre lengths may be determined to this end. E.g. a coarse-fibrous peat may require different treatment than a slightly organic silty clay.

A quantity of soil sufficient to prepare the required number of stabilised soil samples is placed in the mixer. If this exceeds the capacity of the mixer, a larger mixer should be used. It is not acceptable to mix one type of soil in a number of batches. Remove isolated roots and large fibres and coarse material if possible. Mix until the soil is visually homogeneous. In the case of fibrous peat, limit the mixing time to prevent destruction of fibres. If necessary, manually move soil stuck to the mixing bowl to the centre. Note the time used for mixing. Take out two small samples and determine their bulk unit weight and water content. Alternatively the unit weight can be judged from knowledge in the specific area and at the specific depth, preferably from determinations on undisturbed samples.

Choice of sample diameter
Choose the sample diameter based on the coarseness of the mixed soil. In the large majority of cases, 50 mm will be sufficient. Only when the soil contains many coarse particles or fibres should a larger diameter be used.

Preparation of stabilizer
When stabilizer is used which consists of two or more materials, mix these components together in the required proportions and in a quantity sufficient to perform the required tests. For wet mixing, form a slurry by mixing the stabilizer with water to obtain the required water-stabilizer ratio (m/m).

Mixing of soil and stabilizer
A quantity of soil sufficient to prepare the required number of stabilised soil samples for the given soil and a given stabilizer at a given dosage, is placed in the mixer.

Use the bulk unit weight as determined under ”Homogenization of soil” and the required dosage of stabilizer to calculate the necessary amount of stabilizer or stabilizer slurry. Dry stabilizer in the case of dry mixing, and stabilizer slurry in the case of wet mixing, is added to the soil in the mixer. Soil and stabilizer are mixed until the mass is visually homogeneous. In the case of fibrous peat, limit the mixing time to prevent destruction of fibres. If necessary, manually move soil stuck to the mixing bowl to the centre. Note the time used for mixing. Take out two small samples and determine their water content. Protect the mixed soil from drying out before it is applied to form a sample.

For comparable tests within one laboratory on a given soil, varying stabilizer and dosage, it is necessary to adopt the same mixing time.

> *Note*. Differences in the properties of soils and stabilizers and the mixing machines make it impossible to specify a fixed duration of mixing. The most reliable and repeatable measure of the homogeneity of mixing is the visual appearance. However, where possible, a mixing period of 5 minutes should be applied.

Compaction of mixed soil in mould
The compaction should be performed directly after mixing. The time from mixing to finished sample should be kept low. The entire batch of mixed soil must be formed into samples within 30 minutes of mixing. If many samples are to be prepared with the same dosage it can be advisable to split them into two or three batches.

In case a slit mould is used, clamp it or place it in a tightly fitting thick walled tube to prevent lateral bulging during compaction.

Place a layer of mixed soil in the mould to a thickness of approx. 25 mm thick (aspect ratio 0.5 in case of differing sample diameter), prod it and press it in place with a fork. Take care to eliminate bubbles of liquid or air. Compact the layer with the compaction tool. Exert a pressure of approx. 100 kPa three times during approx. 2 seconds, each time with the stamp against the wall of the mould and its rod inclined inwards at approx. 10 - 15°, and rotate 120° along the circumference of the mould each time. Continue with three more such compaction strokes, but now with the rod held vertically, and rotate these strokes 60° relative to the first series. Scarify the surface lightly with a fork, and apply a second layer of mixed soil of approximately equal thickness to the first. Repeat the compaction procedure. Continue to place and compact the mixed soil in this manner, in 4 layers (for moulds with more than

100 mm length perhaps 5 or 6 layers) of approximately equal thickness to slightly above the upper rim of the mould, and trim off excess material above the rim, leaving the upper surface entirely flat. If the mould has a length of more than 100 mm the compaction will have to be done in more than 4 layers.

Alternatively, compaction can be performed with a press, which is calibrated to yield a pressure of 100 kPa. If the same kneading action as with manual compaction is desirable, a metal plate with an inclined base could be fitted to the bottom of the stamp during the first 3 compaction strokes per layer.

> *Note* Some high water content peats are very loose and liquid after mixing with stabilizer. There is no need to compact such material, and it suffices to carefully pour it into the mould.

> *Note* Inclining the stamp increases the kneading action and reduces problems with sticky clays. If necessary, the second bout of 3 strokes may also be with inclined stamp.

Storage
The storage temperature shall be specified in the order to the laboratory. Normally samples are cured and stored in sealed tubes at 18 - 22 °C.

> *Note* The chosen temperature will affect the rate of increase in strength.

> *Note* Normally no load is applied during curing and storage. Strength of stabilised soil generally increases if a load is applied during curing. This is especially applicable to mass-stabilization of surface layers of high water content peat, where efforts are made to apply a surcharge as quickly as possible after stabilization. Separate procedures are available for mass stabilization applications (Cf. Chapter 6.4.3).

Removing sample from its mould
After the specified curing period, note the height of the sample relative to the ends of the mould, and note the roughness of the end surface of the sample. The removal of the samples from the mould should be made with a minimum of disturbance. E.g. in case taped slit moulds have been used, remove the tape from the slit and pry the slit open to allow the sample to be removed. In case of cardboard moulds, peel off the cardboard.

> *Note* Using large force to extrude a cured sample from its mould could be detrimental to sample quality.

Preparation of sample ends
Preparation of sample ends is only needed if the upper end of the sample has become rough during curing: Cut off a small slice from the upper end of the sample to obtain a flat surface perpendicular to its length axis. Alternatively, if only unconfined compression tests or unconsolidated undrained triaxial tests are to be performed on the samples, it is acceptable to smoothen the upper surface with a thin layer of gypsum.

> *Note* Appropriate cutting equipment, e.g. diamond-tipped saws, which apply minimal disturbance to the sample, and ensure perpendicular and flat cuts, must be used.

<u>Reporting</u>
A full report shall be given of the conditions of sample preparation, as follows:

- classification of soil if determined
- origin and quantity of soil
- removal of isolated coarse particles etc. from soil
- specifications of soil mixer, and applied mixing tool, power, r.p.m.'s, mixing time, storage conditions and time
- water content of the homogenized soil
- chosen sample diameter
- specifications of the chemical and physical properties of each stabilizer material as provided by its producer or supplier:
    - composition (m/m): at least CaO, SiO_2 , Al_2O_3 , Fe_2O_3 , MgO, K_2O , Na_2O , SO_3
    - (for unslaked lime record both total and active CaO)
    - reactivity
    - specific surface area (Blaine number)
    - density
    - particle size distribution

- quantity of stabilizer and if applicable proportions of stabilizers
- specifications of soil/stabilizer mixer, and applied mixing tool, power, r.p.m.'s, mixing time, storage conditions and time
- type of moulds used
- if a compaction press is used: description of compaction press: diameter and geometry of stamp, applied pressure
- bulk density and water content of the mixed soil/stabilizer after mixing
- storage temperature and deviations from it during curing

Per sample shall be reported:
- bulk density after compaction and trimming into the mould
- height of sample relative to the top of the mould after curing
- roughness of the top end of the sample after curing
- any difficulty in removing sample from mould after curing
- any irregularities of the sample, e.g. visible holes and large voids, or the bottom end not being entirely flat and perpendicular
- treatment of upper end surface prior to further testing.
- whether top end is cut off and sample height after cutting
- bulk density after removal from the mould

6.4.3 Laboratory procedure for test samples (mass stabilization applications)

<u>Scope</u>

The preparation in the laboratory of samples of soil stabilised by mixing with lime and/or cement-type materials for mass stabilization applications is specified. The focus is on soft soils, which contain organic matter in varying degrees: organic clay, gyttja or peat. The stabilizer material may be cement (e.g. Portland cement or blast furnace slag cement) or a mixture of cement with additives such as ground granulated blast furnace slag, gypsum, lime, or fly ash. The samples serve for investigation of the properties of the stabilised soil, e.g. by means of the unconfined compression test or the triaxial test.

For deep mixing (column) applications, different procedures are necessary for the laboratory preparation of stabilised soil samples, see 6.4.2.

<u>Significance and use</u>

The present procedure is relatively simple and yields samples of stabilised soil suitable for the determination of strength and stiffness by means of laboratory strength tests on cylindrical samples such as the unconfined compression test, various kinds of triaxial test and direct shear tests. Other properties, such as permeability, physical and chemical durability, and compressibility may also be determined on such samples. The method yields samples, which may be used in determining type of stabilizer and dosage for mass stabilization projects. The samples obtained by the method however do not completely reflect the structure of soil stabilised in-situ by common mass stabilization techniques. Conditions of mixing and curing in the laboratory deviate significantly from field conditions, and consequently laboratory strength and stiffness determined on samples prepared by this procedure will likewise deviate from field values. However, when planning a mass stabilization project, a comparative laboratory investigation of the properties of different samples prepared with various stabilizer materials in varying dosages and after varying curing periods, is a useful, often indispensable aid. Further, empirical rules can be developed to allow for the differences in e.g. strength and stiffness between field-stabilised and laboratory-stabilised material. It is usual to produce a number of trial pads ahead of the actual project. Based on the results of the laboratory programme, a few stabilizer combinations and dosages can be applied, and the results are used to assist the final choice and to determine the engineering parameters for use in the final design.

The present procedure gives no guidelines as to the number of tests that should be performed, and the number of variables (e.g. different stabilizers, dosages, length of curing period, etc) that should be tested. These should be carefully planned when defining the laboratory investigation.

<u>Materials and equipment</u>

Soil

Soil is obtained from the site under investigation. It may be obtained by large diameter tube samplers such as the SGI Peat Sampler or by soil sampling devices such as tube and piston samplers and the continuous Delft sampler. Auger samples are acceptable if it can be shown that intermixing of different soil layers is kept within acceptable limits. Large diameter
(>20 cm) augers have the advantage of allowing a large quantity of soil to be collected, while the soft soils in question are usually easily penetrated by them.

Stabilizer
Stabilizers are materials with hydraulic properties such as Portland cement, blast furnace slag cement, ground granulated blast furnace slag, fly ash, slaked or unslaked lime, and gypsum (anhydrous, demi-hydrous or di-hydrous). The stabilizer used in the laboratory preparation of samples must be representative of the materials to be used in-situ, and must be adequately stored such that their properties are not impaired by exposure to moisture or moist air or extreme temperatures. If stabilizer material has been stored for long periods, its reactivity should be checked.

A stabilizer can be a mixture of two or more stabilizer materials. Filler materials such as sand, silica fume etc. can also be mixed in.

Some stabilizers, notably unslaked lime, have caustic properties, and proper safety precautions and procedures shall be adhered to in dealing with them.

Equipment
- Mixing machine (dough mixer or kitchen mixer) of sufficient capacity to mix soil for the entire test programme (usually 20-50 liters).
- Mixing machine of sufficient capacity to mix a batch of soil with one binder
- Bowl for mixing
- Balance with 0,1 g weighing accuracy up to a measuring range of 2 kg
- Cylindrical moulds for test samples. The size of the mould: inner diameter 68 mm and height 200-300 mm. Here, the test samples will relatively well represent the structure of peat. In average, the test samples will have a weight of about 0,6-0,9 kg
- Loading stamps, e.g. equipped with plastic loading caps to direct load on the top of the test sample. The loading stamps will have a weight of about 6,5 kg. The diameter of the loading stamp should be 2-3 mm less than that of the mould
- Filter stone at the bottom of the mould
- Filter to be used on the top of the test sample (under the loading stamp)
- Loading rack to keep the test samples under load in a vertical position
- Water vessel to simulate the moisture conditions during loading
- Porous mat in the water vessel
- Fork: a kitchen fork the prongs of which may be bent at right angles over a length of approx. 15 mm.

Both the top and the bottom of the sample shall have access to water during the storage time.

The ends of the cylindrical moulds must be flat and perpendicular to the length axis.

<u>Preparation and storage procedure</u>

Homogenization of soil

> *Note* Details of the preparation method, such as type of mixing machine and mixing tool, power and r.p.m.'s of the mixing machine, duration of mixing etc. are not specified, but must be chosen on the basis of local experience with the soil and the available equipment. Classification of the soil in an early stage can assist the choices. Bulk unit weight, water content, organic content, degree of humification, particle size distribution and maximum fibre lengths may be determined to this end. E.g. a coarse-fibrous peat may require different treatment than a slightly organic silty clay.

Homogenization of soil should be performed according to following procedure:
A quantity of soil sufficient to prepare the required number of stabilised soil samples is placed in the mixer. If this exceeds the capacity of the mixer, a larger mixer should be used. It is not acceptable to mix one type of soil in a number of batches. Remove isolated roots and large fibres and coarse material if possible. Mix until the soil is visually homogeneous. In the case of fibrous peat, limit the mixing time to prevent destruction of fibres. Note the time used for mixing. Take out 2 small samples

and determine their bulk unit weight and water content. Alternatively the unit weight can be judged from knowledge in the specific area and at the specific depth, preferably from determinations on undisturbed samples.

Choice of sample diameter
Choose the sample diameter based on the coarseness of the mixed soil. In the large majority of cases, 68 mm will be sufficient. Only when the soil contains many coarse particles or fibres, a larger diameter should be used.

Preparation of stabilizer
When a stabilizer is used which consists of two or more materials, mix these components together in the required proportions and in a quantity sufficient to perform the required tests.

Mixing of soil and stabilizer
A quantity of soil sufficient to prepare the required number of stabilised soil samples for the given soil and a given stabilizer at a given dosage, is placed in the mixer. Each prescribed mixture should be tested with 2 parallel test samples.

Use the bulk unit weight as determined under ”Homogenization of soil” and the required dosage of stabilizer to calculate the necessary amount of stabilizer. The binder quantity is given (as kg/m^3) relative to the wet mass of the peat. For example:

- The density of peat is 1000 kg/m^3;
- The prescribed binder quantity is 150 kg/m^3;
- 150 g binder is needed for each 1000 g of peat.

The stabilizer is added to the soil in the mixer. Soil and stabilizer are mixed until the mass is visually homogeneous, normally 2-5 minutes. Note the time used for mixing.

For comparable tests within one laboratory on a given soil, varying stabilizer and dosage, it is necessary to adopt the same mixing time.

> *Note*. Differences in the properties of soils and stabilizers and the mixing machines make it impossible to specify a fixed duration of mixing. The most reliable and repeatable measure of the homogeneity of mixing is the visual appearance. However, where possible, a mixing period of 5 minutes should be applied.

Compaction of mixed soil in mould
The compaction should be performed directly after mixing. The time from mixing to finished sample should be kept low. The entire batch of mixed soil must be formed into samples within 30 minutes of mixing. If many samples are to be prepared with the same dosage it can be advisable to split them into two or three batches.

- Place a filter stone at the bottom and wrap and bind the net cloth around the bottom of the mould.
- If the material mix is liquid no compaction is required. The stabilised mass can be “poured” or placed and levelled into the moulds. In case the mixture is solid it is compacted into the moulds in 5 – 6 layers. In-between the compaction the layers are loosened or ‘bound to each other’ (e.g. with help a fork).
- Determine the bulk density of the compacted test samples before loading (later also after loading). The water content is determined when required.

Storage/loading
The following procedure is recommended:
1. After compaction a filter is set on top of the test sample in the mould
2. The moulds are set vertically into the rack, on the porous mat in the water vessel – the test sample will remain wet during the loading period.
3. The loading stamp is placed on top of the sample. The magnitude of the loading has to be determined when preparing the test. For example if the required load should be equivalent to an embankment with a height of 1 metre (18 kPa) in the field, the load on the test sample should be 6,5 kg (If sample diameter is 68 mm).

4. The storage temperature shall be specified in the order to the laboratory. Normally samples are cured and stored in sealed tubes at 18 - 22 °C.
5. The compression of the test sample is measured immediately after the start (5 seconds) of the loading test. After this the compression is measured after 1 day, 3 days … etc. until there is no change of compression.

Removing sample from its mould
After the specified curing period, note the height of the sample relative to the ends of the mould, and note the roughness of the end surface of the sample. The removal of the samples from the mould should be made with a minimum of disturbance. Determine the bulk density of the compacted test samples after the specified curing period under load.

Preparation of sample ends
Preparation of sample ends is only needed if the upper end of the sample has become rough during curing: Cut off a small slice from the upper end of the sample to obtain a flat surface perpendicular to its length axis. Alternatively, if only unconfined compression tests or unconsolidated undrained triaxial tests are to be performed on the samples, it is acceptable to smoothen the upper surface with a thin layer of gypsum.

> *Note* Appropriate cutting equipment, e.g. diamond-tipped saws, which apply minimal disturbance to the sample, and ensure perpendicular and flat cuts, must be used.

<u>Reporting</u>

A full report shall be given of the conditions of sample preparation, as follows:
- classification of soil if determined
- origin and quantity of soil
- removal of isolated coarse particles etc. from soil
- specifications of soil mixer, and applied mixing tool, power, r.p.m.'s, mixing time, storage conditions and time
- water content of the homogenized soil
- chosen sample diameter
- specifications of the chemical and physical properties of each stabilizer material as provided by its producer or supplier:
  - composition (m/m): at least CaO, SiO_2 , Al_2O_3 , Fe_2O_3 , MgO, K_2O , Na_2O , SO_3
  - (for unslaked lime record both total and active CaO)
  - reactivity
  - specific surface area (Blaine number)
  - density
  - particle size distribution
- quantity of stabilizer and if applicable proportions of stabilizers
- specifications of soil/stabilizer mixer, and applied mixing tool, power, r.p.m.'s, mixing time, storage conditions and time
- type of moulds used
- if a compaction press is used: description of compaction press: diameter and geometry of stamp, applied pressure
- bulk density and water content of the mixed soil/stabilizer after mixing.
- storage temperature and deviations from it during curing

Per sample shall be reported:
- bulk density after compaction and trimming into the mould
- height of sample relative to the top of the mould after curing
- roughness of the top end of the sample after curing
- any difficulty in removing sample from mould after curing
- any irregularities of the sample, e.g. visible holes and large voids, or the bottom end not being entirely flat and perpendicular
- treatment of upper end surface prior to further testing.
- whether top end is cut off and sample height after cutting
- bulk density after removal from the mould
- the compression during the curing time

6.4.4 Testing methods

The following ETC5 documents are applicable to many of the tests likely to be performed on the samples prepared by the procedures in 6.4.2 and 6.4.3:

- *ETC5-E2.97* Laboratory method for determination of unconfined compressive strength: Unconfined compression test on cohesive soils
- *ETC5-E3.97* Laboratory method for determination of undrained shear strength: Unconsolidated undrained triaxial test
- *ETC5-F1.97* Stress-strain testing: Methods for consolidated triaxial compression tests on water-saturated soils
- *(ETC5-F2.97* Laboratory methods for direct shear tests)
- *ETC5-G1.97* Permeability testing: Determination of soil permeability by constant and falling head
- *ETC5-D1.97* Compressibility testing: Incremental loading oedometer test and also CRS -test

6.4.5 Evaluation

Evaluation of the results of the laboratory mix design programme will usually concentrate on unconfined compressive strength q_u , stiffness E, and permeability k.

A typical stress - strain curve from an unconfined compression test is shown in figure 6.5. The compressive strength q_u is taken as the peak value at P found in unconfined compression tests or undrained triaxial tests.

The stiffness E is taken from the pre-failure part of the curve. Often the initial strain will contain bedding deformation, and the figure shows how to correct for this. The usual value of stiffness derived from the unconfined (relative values) or triaxial tests is the E_{50} value at a stress equal to 50% (point C) of the failure stress.

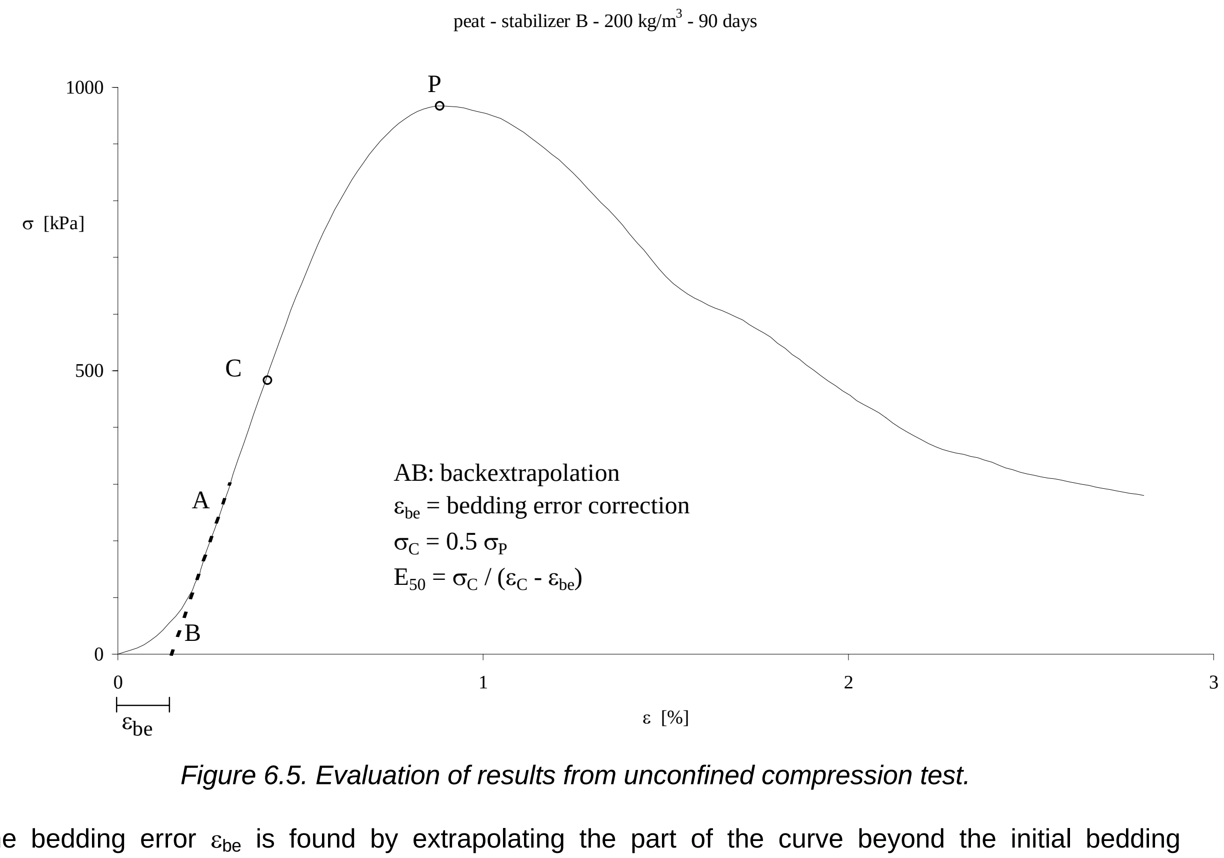


Figure 6.5. Evaluation of results from unconfined compression test.

The bedding error ε_{be} is found by extrapolating the part of the curve beyond the initial bedding deformation, linearly back to the horizontal axis. This yields point B from which the stiffness is measured.

It is common in the engineering of stabilised soil projects to determine stiffness E_{50} from a correlation with the unconfined compressive strength q_u , preferably from drained triaxial tests. A fairly linear relation between E_{50} and the strength exists. Values of E_{50} in the range of 100 times the strength up to

200 has been reported. Figure 6.6 shows such a correlation for two projects, including various soils and various stabilizers and dosages.

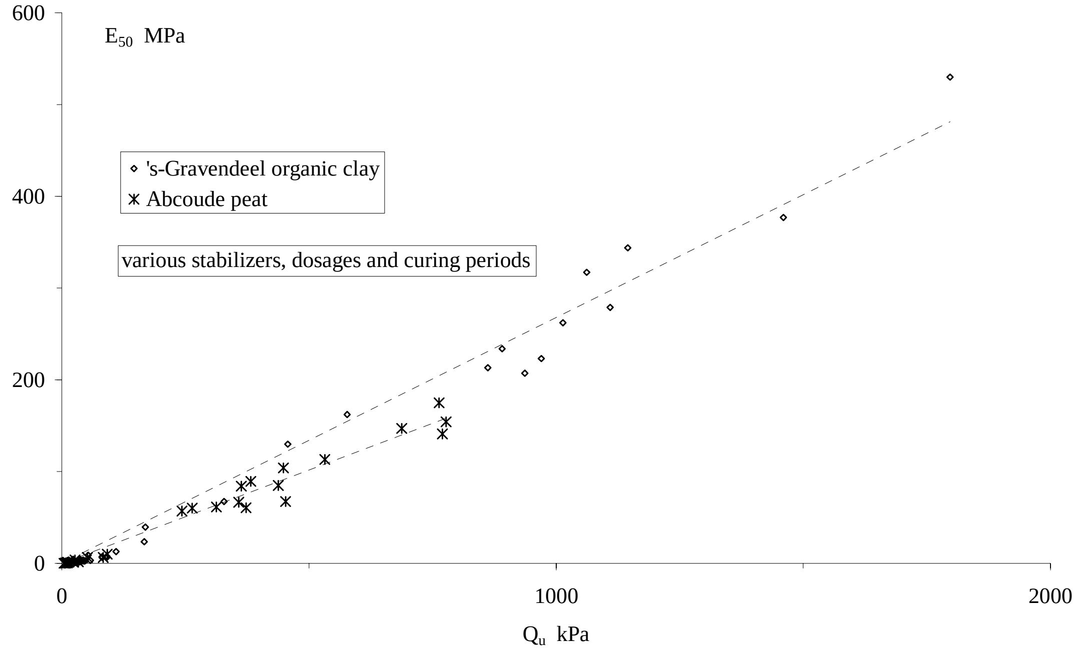


Figure 6.6. Correlation between E_{50} and unconfined compressive strength.

It is often useful to plot strength qu against the dosage for a given stabilizer and soil. The following figure reveals the existence of a threshold dosage below which the increase of strength is likely to be very minimal. In other words: every extra kg of stabilizer above the threshold yields a disproportionately strong increase of attainable strength. In figure 6.7 the threshold would be some 100 kg stabilizer per m^3 of soil. If this is true for laboratory samples which are subjected to ideal mixing and curing conditions, then it is unlikely that lower dosages than the threshold value in the field would be very effective, although due to the variable mixing, locally in a column high strengths could still be attained.

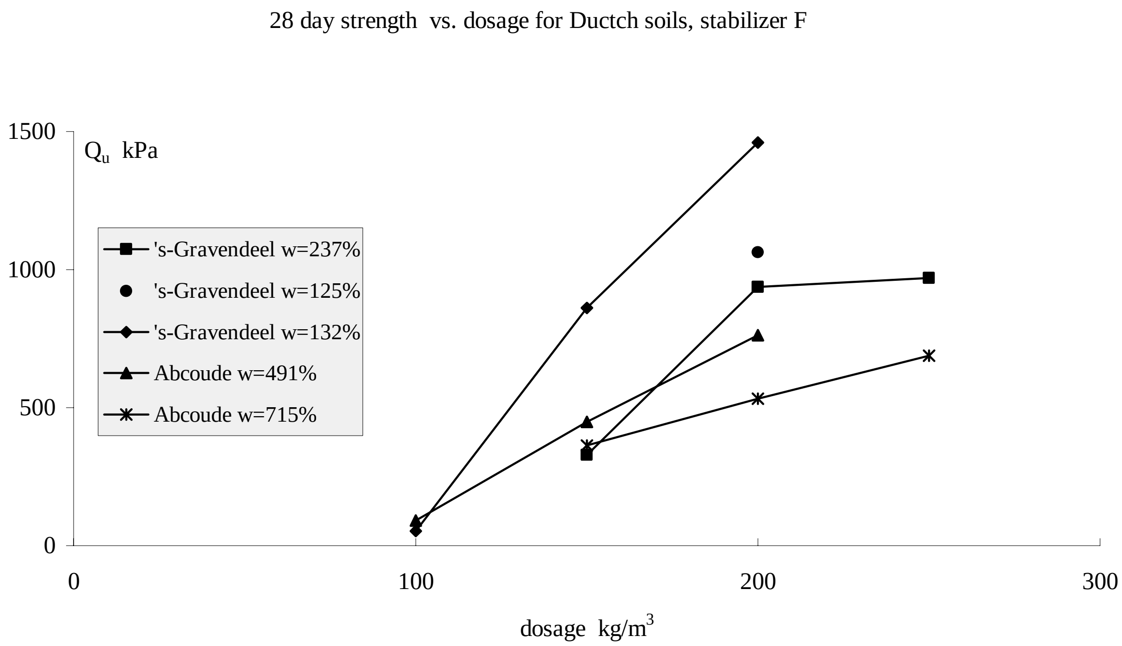


Figure 6.7. Correlation between E_{50} and unconfined compressive strength.

Another example of the influence of the quantity of binder is shown in figure 6.8 giving the influence of the binder quantity at stabilization of peat with cement-slag as binder.

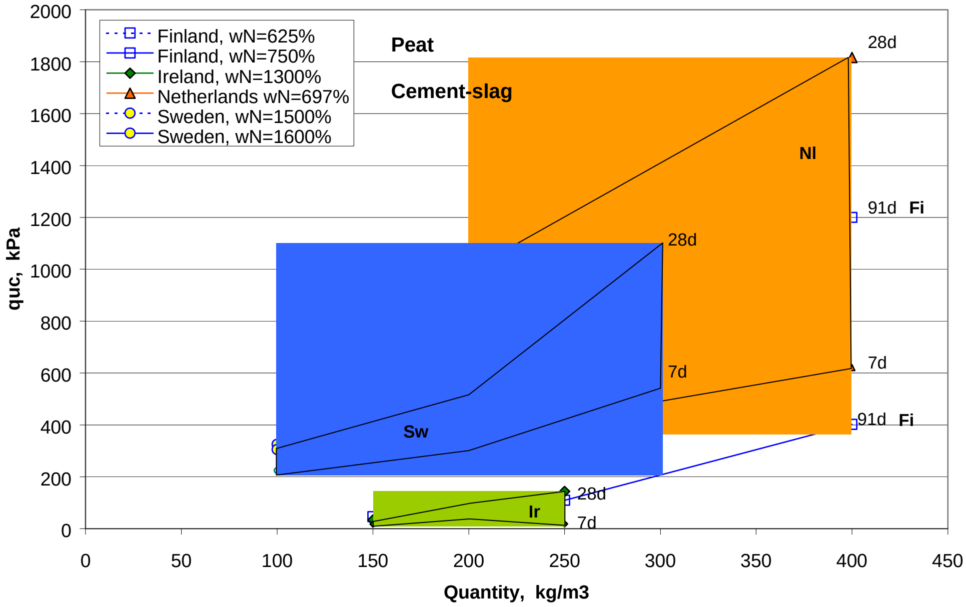


Figure 6.8. Influence of the quantity of binder to the unconfined compressive strength.

Permeability of stabilised soil can be derived preferably from permeability tests. If derived from oedometer tests in the usual manner applying Taylor's or Casagrande's interpretation of the primary part of the settlement curve, a somewhat different permeability is obtained due to a lower degree of saturation.

Consolidated drained triaxial tests on stabilised soil should be used to determine the effective strength parameters such as φ' and c′. From undrained triaxial tests it is possible to determine the increase of column strength with depth. Often such tests show a tendency to develop excess pores pressures almost equal to the effective cell pressure (i.e. cell pressure relative to back pressure). Effective stresses then tend to be zero in the horizontal direction, and the sample usually fails. Sometimes, as shown in figure 6.9 (curve for lowest consolidation pressure), compression and hardening continue for quite a while with virtually zero horizontal effective stress. In this condition, φ' cannot be determined from undrained tests- it would turn out at 90°! Such behaviour may well reflect actual field behaviour, and allowance for it would need to be made in calculating column strength.

In all evaluations of the laboratory tests it must be remembered that laboratory prepared stabilised soil samples are likely to exhibit very different behaviour from stabilised soil in the field. Overall strength of stabilised organic clay and peat is most often considerably less in the field than for laboratory prepared samples. This is different from the situation in inorganic soft clays where field strength sometimes surpasses laboratory values. Permeability of stabilised organic soils and peat has been found to be lower for laboratory samples than for cores obtained from columns, but otherwise relatively little is known about this relationship.

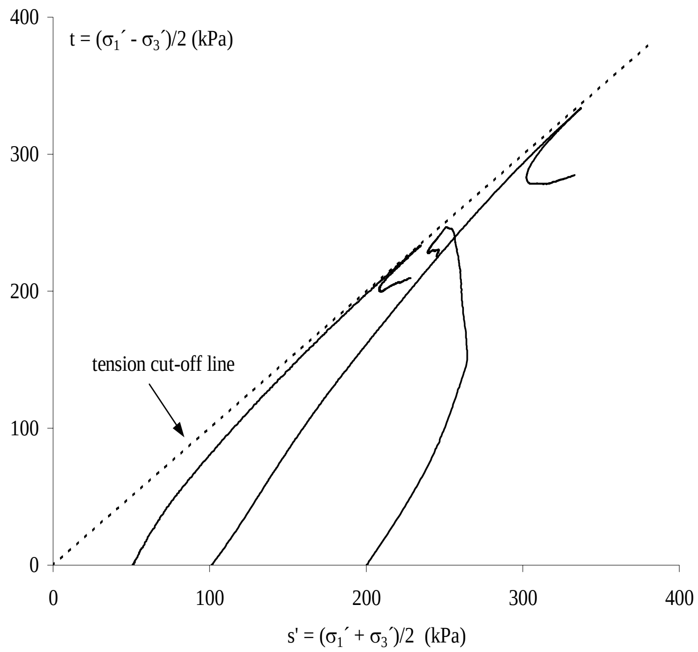


Figure 6.9. Triaxial test on stabilised soil.

6.5 Field trials

6.5.1 Design of test program

The primary objectives of installing trial columns or trial volumes of mass stabilisation are to perform tests to determine the properties in situ and based on these results make the final choice of type and amount of binder and installation method. Important aspects to consider when making this choice are:

- strength of stabilised soil and its increase with time
- stiffness of stabilised soil and its increase with time
- homogeneity of stabilised soil
- environmental impacts of the stabilised soil
- the amount of load the columns must be able to sustain at a specific (curing)time
- costs for binder
- installation costs

When making the final choice it should also be remembered, as stated in chapter 4 that too high strength and stiffness of the columns are not necessarily desirable since the underlying design philosophy is that stabilised and unstabilised soil interact.

A number of columns with the same composition and installation technique must be tested in order to have sufficient data making the results reliable. If a road or railway embankment, or similar, is to be constructed it may also be necessary to perform field trials at several locations due to varying soil profiles and other geological conditions. Obviously, if all aspects listed above are to be studied the number of trial columns may become quite large. Therefore, the size of the test program depends on the type and size of the project.

Some general recommendations for the scope of tests of mechanical properties are:

- The tests shall cover the whole length of the trial columns. The properties of the stabilised soil vary for different soil types (layers).
- For trial columns of a specific composition and installation technique the tests should preferably be performed at curing time(s) corresponding to the time(s) when the column must carry specific load(s). In order to assess the strength-time relation the tests should be performed at least at two different curing times and the results combined with results obtained from the laboratory investigations. Common curing times for testing are one or several of 7, 14, 28, 56 and 90 days.
- For trial columns of a specific composition, installation technique and curing time, a minimum of 5 columns should be tested in order to make the results reliable.

At the construction of the whole stabilization a number of columns should be tested as production control, see Chapter 9. The size of this test program depends on the type and size of the project. The number of test columns should be at least 0,5% of the total number of columns in the project for large projects and at least 1,5% for small projects.

Some general recommendations for the scope of tests of environmental aspects are:
- Leaching tests combined with ground water monitoring is recommended for assessment of the environmental suitability of a stabilising object when lacking results from previous use of the actual binder in the actual soil conditions.
- Tests shall include measurements of parameters in the groundwater that are characteristic for the binder(s) such as pH and electrical conductivity in the downstream gradient from the stabilised area. This determines the rate of transport and the distribution of the area influenced by the stabilization. To ensure that the content in the groundwater is representative for the long-term leaching quality, sampling of potential harmful elements should be done after at least 90 days since the leaching quality is changing rapidly at the initial phases of curing.
- In general it is recommended that chemical and environmental tests of the soil and mixtures of soil and binders are carried out in the laboratory on field samples.

6.5.2 Testing methods

The mechanical properties of the stabilised soil may be checked in-situ with various types of penetration testing methods. Sampling, using core-drilling may also be performed and the samples tested in the laboratory. Visual inspection of the column homogeneity may be performed through test-pit digging, possibly in connection with sampling for laboratory investigations of e.g. the chemical composition. Extraction of entire columns, and subsequent inspection and testing, may also be done using large split-tube samplers.

The most common procedure is to check the mechanical properties by penetration tests. A specially designed penetrometer is used, see Chapter 7. The penetration can be made downwards or upwards. In the later case the penetrometer is installed below the column by the column mixing equipment. It is important to take into account that penetration upwards (PORT-test) is however only suitable for testing columns. Also CPT-test may be used, sometimes from the bottom of a gradually prebored hole because CPT cone tends to deviate out of the columns especially if the strength varies considerably.

Concerning environmental tests the sampling of soils shall be performed in a way that the original composition of the soil and its porewater is preserved.

Tests of chemical parameters in the soil of importance for the strength of the soil or for the necessary amount of binder shall include water content and organic content. A description of the sampling procedure is presented in 6.5.3 below.

6.5.3 Manual for sampling, storage and chemical analysis of soil, binder and stabilized soil

<u>Introduction</u>
The intention is to analyse chemical properties that are important to soil strength, durability and to give sufficient data for an environmental assessment in relation to the original soil.

<u>Sampling and storing</u>
Samples are to be taken in-situ by a piston sampler and the samples (with sampling tubes) should be put in double plastic bags. The bags should be rinsed with nitrogen when the samples are put in the bags. The soil samples should be stored as they are, i.e. in the sampling tubes until extraction of porewater. The samples used for analysis of the soil and the original porewater should not be older than a few weeks.

The mixing of soil and binder should be done within a short time span to minimise the amount of oxygen to the samples. After mixing the samples should be stored cold (5 – 10 ^{o}C) for at least 90 days. This will ensure that the hydration of binder have stopped and the constituents in the porewater will be constant over time.

It is recommended that the samples are not exposed to air more than 0.5 h during the technical investigations in order to preserve the chemistry of the samples. The extraction of porewater and subsequent chemical analysis should commence immediately after such investigations.

In any case it must be ensured that both chemical and geotechnical parameters are available for the same set of samples.

Extraction of porewater

Extraction of soil porewater should be done with an oedometer or triaxial cell. Other in-situ systems are possible for the extraction of porewater for the original soil, but since an in-situ procedure for the stabilised soil may give non-representative samples it is recommended to extract porewater from the stabilised soil from laboratory samples and from the original soil with a similar procedure.

Porewater in the soil should be extracted and analysed if detailed information on the environmental properties is needed or if the content of chlorides or organic matter such as humic acids in the porewater is suspected to cause a poor stabilisation effect. If a detailed environmental analysis is needed then precautions should be taken to minimise contamination of the samples. The filter stone of the oedometer and/or the filter of the triaxial cell should be washed in nitric acid (HNO_3) by letting the filter material stay in the acid overnight. The concentration of the acid should be 0,1 M HNO_3 or more if the material is resistant to the acid. The next day the filter material should be rinsed with distilled water or with water of equivalent quality, until the pH of the water is normal (a check with pH-paper is sufficient).

When the porewater is extracted from the original soil or the stabilised soil the outflowing water normally will come into contact with the air. This should be avoided. For the triaxial cell a device consisting of a tube leading the porewater through a perforated cap can be used. Nitrogen should flush the bottle while porewater is collected.

Finally the sampled water should be filtered through a filter with a pore size of 0.45 µm. This pore size is a conventionally applied size for the separation of the solid and dissolved phases.

Analysis

Porewater

pH, Chlorides, humic acids/total organic carbon, concentrations of trace elements (Cf. Note 1 below), for organic soils total nitrogen should be analysed.

Soil

- pH (measured with electrode)
- Solid phase analysis with concentrations of major and trace elements (Cf. Note 2 below)
- Ion exchange capacity
- Sulphide content/total sulphur (additional amount of binder may be needed)
- Total availability tests and analysis of leachates according to (Cf. Note 1 below) together with chlorides, and for organic soils total nitrogen.

Stabilised soil

- pH (titration of hydroxides)
- Solid phase analysis with concentrations of major and trace elements (Cf. Note 2 below)
- Sulphide content/total sulphur (additional amount of binder may be needed)
- Total availability tests and analysis of leachates (Cf. Note 1 below) together with chlorides, and for organic soils total nitrogen.

If the results of the solid phase analysis or of the total availability tests are above national guidance or limiting values, other leaching tests should be done. Depending on the permeability of the material either column or diffusion test could be of interest. Leaching tests on the stabilised soil should be compared with leaching from the original soil.

Note 1 Analyse package including main elements in the porewater such as sodium (Na), potassium (K), calcium (Ca), magnesia (Mg) and including total sulphur (S), and trace elements such as Al, As, Ba, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, S, Zn.

Note 2 Analyse package with an estimation of minerals in the soil SiO_2 Al_2O_3 CaO Fe_2O_3 K_2O MgO MnO_2 Na_2O P_2O_5 TiO_2 as well as loss of ignition (LOI) giving the overall concentration of organic material in the soil and trace elements: As, Ba, Be, Cd, Co, Cr, Cu, Hg, La, Mo, Nb, Ni, Pb, Sc, Sn, Sr, V, W, Y, Yb, Zn, Zr.

6.5.4 Evaluation and things to remember

Generally

The trial columns are normally installed very early in a project and the machinery may not be trimmed ideally. Thus the column quality may be lower than in "production". On the other hand, the trial columns may be installed with special efforts since the outcome of the tests is of outmost importance. Thus the column quality may me higher than in "production". Nevertheless, when evaluating the results it should not be forgotten that the properties of the columns improve with the curing time.

Reverse penetration testing and penetration testing downwards:

- The shear strength of the stabilised column is evaluated N_c= 10
- As 1/10 of the net specific resistance (after reduction for wire-friction) at the specially designed penetrometer
- Use vane width only slightly smaller than the column diameter when testing columns. Normally 0.1 m smaller.
- Use a speed of 20 mm/sec.
- Make sure that wire strength counter weight and pull out capacity of machinery are sufficient.
- For reverse penetration testing: make sure that the anchor is pushed down about 2 m below column tip for reverse penetration testing in order to allow for consideration of wire-friction when evaluating column properties. Pull the wire (and anchor) about 0.5 m within normally 2 days of curing in order to reduce wire-friction.
- Gravel and stones in the working platform may sink into the column during installation. If they are hit during penetration testing the resulting resistance may reflect the resistance of pulling/pushing the anchor and the gravel/ boulders through the column, i.e. a too high strength is evaluated.
- In penetration testing downwards the probe may steer out of the column at greater depths, especially if the column is not homogeneous. In that case preboring with 57/64 bit or 75 mm casing can be used to steer the penetrometer.

CPT-penetration testing:

- Common CPT is very suitable for testing stabilised columns if the average undrained shear strength is 50 – 1000 kPa. Because of the small diameter of the cone (10 cm^2) the interpretation of the results should be based on a large number of CPT tests, minimum 10. Statistical analysis is recommended to calculate the mean value and the standard deviation from the results at different depths. CPTU equipment can also be used, but there is then a higher risk to damage the probe when the penetrometer is bending in inhomogeneous columns.
- CPT probe may also steer out of the column at greater depths. In deep columns it is however very easy to detect the exact depth when the CPT-probe is steering out of the column. It is then possible to lift up the CPT rods and to drill a small casing (75 mm) down to the depth where CPT steered out. After preboring CPT is continued till the next time the CPT steers out of the column. Preboring can be used again if needed. Using preboring with casing it is possible to test even 20 m long columns.
- Cone factor for estimating qu is N_c=10 - 13
- Preboring must also be used if there are gravel or stones at the top of the columns.

7. Construction

7.1 Introduction

The construction of deep in situ soil mixing can be carried out either in columns or by mass mixing volumes of soil. The mixing can use either the dry or the wet methods that are used in Europe, USA and the Far East. Mass stabilisation uses dry mixing and is currently applied in Finland and Sweden

This chapter considers the construction of deep soil mixing which comprises the following activities:

1. Pre construction considerations of:
   - mobilisation of equipment and materials to the site,
   - storage of the materials,
   - temporary works to enable the mixing equipment to work efficiently,
   - the site blending of binders,
2. The soil mixing:
   - Column mixing
   - Mass mixing.
3. Monitoring and instrumentation:
   - monitoring of the mixing process
   - control of the delivery of binders
   - output of monitoring data
4. Environmental considerations
5. Quality assurance:
   - Production controls
   - Post construction testing

7.2 Pre-construction considerations

It is assumed here that soil investigations, laboratory tests as well as design of stabilisation, as described in previous chapters, have been made and that the client and local authorities have approved the construction work.

Before the site can be prepared for construction, a number of factors must be checked. Although all sites are to some extent different, in most cases, the following need to be addressed:

- accessibility to the stabilisation area;
- bearing capacity of ground for the support of the mixing equipment;
- obstacles at, below and above ground level;
- objects around the site which can be harmed or damaged by construction works.

Further, the site must be planned so that the stabilisation works do not interfere with other site activities. This is sometimes difficult to achieve since the stabilisation construction equipment is heavy and requires a large space for operation. The stabilisation may become more time-consuming and expensive than expected if conflicts with other construction works occur, for example piling or filling. Good and careful planning of the complete project can prevent this.

In particular, the logistics providing storage and feeding of binders must be well planned. Having the binder storage remote from the stabilisation site will cost in production time. Storage containers must be easily accessible both the delivery transport to the site as well as by the mixing equipment. It is possible that these two requirements are in conflict and a compromise has to be chosen. An alternative would be to pump the binders through a flexible pipeline from the storage silos to the mixing machine.

7.2.1 Accessibility to the stabilisation area

Access to the area of the site to be stabilised needs to be assessed for delivery of plant and materials. The areas for storage and blending of materials need to be allocated so as not to impede the progress of the stabilisation plant either because they are too distant from the stabilisation area or are in an area to be stabilised. This situation is particularly difficult for long narrow sites such as road or rail widening schemes.

7.2.2 Bearing capacity of ground for the support of the mixing plant

For all the stabilisation processes the machinery and plant are heavy (50 to 80 tonnes) and very tall (up to 20 m). Therefore the ground on which they operate must provide a stable base. Since the ground is to be stabilised it follows that it is not very strong so in general to provide a stable working surface a blanket granular material is placed and rolled into a flat working platform. This working platform will spread the load of the equipment and thereby reduce the bearing pressure imposed and provide sound working base. Usually the working platform is placed on a layer of geotextile to keep the granular material from being pressed into the ground. Because the stabilisation will take place through the working platform it may be possible to incorporate it with the geotextile into the design of the subsequent structure. Care must taken in the selection of the geotextile that it can be penetrated by the mixing tool and if used as part of the structure will function after being punctured during the soil mixing.

7.2.3 Obstacles at, below and above ground level

Obstacles that impede the progress of the work can take many forms but the main ones are overhead power cables, which restrict the operation of the stabilisation plant, and old or working underground construction (tunnels, culverts, pipelines or old foundations). However all obstacles should be clearly identified at the site investigation stage of the works.

7.2.4 Adjacent sites which could be affected

Consideration should be given to the effect of the soil mixing process on adjacent sites. Accidental spillage of binders in powder form could be carried by the wind to damage crops or, in the case of binders such as lime, people. If the adjacent sites contain steeply sloping ground the soil mixing could reduce stability during the mixing and hardening of the mixed soil when it is at its weakest. Heave can be a problem with some mixes with up to 50% of the added volume and this could affect an adjacent site. The volume of heave can be controlled by, for example trenching around the stabilised area, slowing down the mixing speed and/or changing the sequence of production.

7.3 The soil mixing

The soil mixing is carried out by mixing in binders in either powder form (for dry mixing) or slurry form (wet mixing). The deep mixing is usually carried out by mixing in columns and shallow mixing (down to about 3 m depth) by mass mixing.

7.3.1 Typical plant and other requirements

The typical plant used will be described in regard to the construction process and production of stabilisation.

<u>Deep soil mixing - Dry method</u>
Figure 7.1a shows typical deep dry mixing plant with on-board binder material silos, air drier and compressor to produce compressed air to transport the binder to the mixing tool. Other designs for deeper work have the binder silos, air drier and compressor on a separate self propelled chassis (see figure 7.1b). The chassis is connected to the mixing machine by an umbilical through which passes the binder, under compressed air, and the monitoring information from the binder mixing and supply rate. The deep mixing machines weigh between 50 and 80 tonnes and have masts which can be up to 20 m high.

Figure 7.1a. Deep dry mixing plant with on-board binder silos, air drier and compressor.

Figure 7.1b. Deep dry mixing plant with separate binder silos, air drier and compressor.

<u>Deep soil mixing - Wet method</u>
The deep wet mixing equipment is shown in figure 7.2 including the separate mixing and holding tanks and pump which is connected to the deep mixing rig by flexible pipeline. The mixing is by high shear colloidal mixers to ensure each binder particle is dispersed into the slurry. The holding tanks have paddle agitators to keep the binders from settling out of the slurry. The deep mixing plant has similar dimensions to those used for dry mixing.

(a)

(b)

Figure 7.2 (a) Deep wet mixing plant with (b) separate mixing and holding tanks and pumps.

Mass mixing

The mass mixing equipment, shown in figure 7.3, is typically attached to the arm of a crawler mounted back actor excavator instead of the excavation bucket. The binder is supplied from a separate unit which houses the binder silos, compressor, air drier and supply control instrumentation. The mass mixing machine typically weighs about 20 tonnes and have a travel height of up to 7 m.

Figure 7.3. Mass soil mixing equipment working, above and below the mixing arm and mixing tool on the groud surface.

Mixing tools

Figure 7.4. Mixing tools for deep dry mixing.

Typical mixing tools used in the deep dry mixing are shown in figure 7.4; they usually consist of a single nozzle for the binder delivery, a horizontal and curved or angled cutting blade. These tools vary in size but are usually made to produce mixed columns in the 500 mm to 800 mm diameter range.

Figure 7.5. Mixing tools for deep wet mixing.

Figure 7.5 shows typical tools for wet mixing, having one or more mixing blades with teeth fitted and one or more nozzles for the binder delivery. The wet mixing tools tend to be of a larger diameter with consequently thicker blades with binder delivery nozzles along the blades. The wet soil mixing tools also vary in size but can be made to make columns up to 2.4 m diameter.

Figure 7.6. Deep mixing tool for dry mass mixing.

The mixing tools for the mass mixing (shown in figure 7.6) are about 800 mm in diameter and resemble a ships propeller but with a binder delivery nozzle at the centre.

The mixing tools are under continued development and each contractor will have a design appropriate to the soil being mixed.

7.3.2 Production of the binder

The flow chart in figure 7.7 shows the process the binder materials progress under go. The chart also shows that for the dry mix method the processes from the blending of materials to the use of the binder may be contained in one or two items of plant. For the wet method there will need to be separate items of plant.

The wet mix process blends the materials with water in a high shear mixer to form a slurry at the design water to solids ratio. The binder slurry is then transferred to reservoirs that continually agitate the slurry to ensure that the constituents of the mix do not separate. The binder slurry is then pumped at the required flow rate to the deep stabilisation machine.

The dry method uses dry materials and usually dried compressed air as transportation media. The materials are fed into a stream of compressed air and the air binder mix is blown directly to the mixing tool of the stabilisation machine.

The proportion of binders used in the wet mixing is controlled by quantities of materials added to the high shear mixer. In the case of the dry mix method the binders are stored in separate silos and the feed rate into the air stream adjusted until the rate of loss of the material from the silos is as previously calculated to give the correct mix proportions. The instrumentation and monitoring needed to achieve the correct control are described in Section 7.4.

7.3.3 The stabilisation process

In the deep stabilisation process the soil is mixed in columns. For both wet and dry processes the binder is injected into the soil through a hollow pipe to a nozzle in the mixing tool. With dry mixing, binder is fed to the mixing tool only as it is withdrawn from the target depth of mixing whereas with the wet mixing the binder is supplied during both penetration to and withdrawal from the target mixing depth. By rotating the mixing tool and injecting the binder through the soil is mixed with the binder and a soil mixed column is formed as the pipe is lifted.

In the dry mixing the compressed air used to deliver the binder to the mixing tool simply exhausts at the mixing tool nozzle, leaving it to disappear through cracks and fissures in the ground. This sometimes causes a temporary heave of the ground surface. A 5 to 10 cm heave is not uncommon at construction works in soft clay. In the wet mixing method the addition of the wet binder slurry can cause heave or production of spoil at the surface. In practice the spoil is replaced in the hollow left by the withdrawal of the mixing tool. The degree of spoil production appears to be related to the ratio of area to be treated to the sum of the areas of the tops of the columns. As this ratio rises so does the volume of spoil produced.

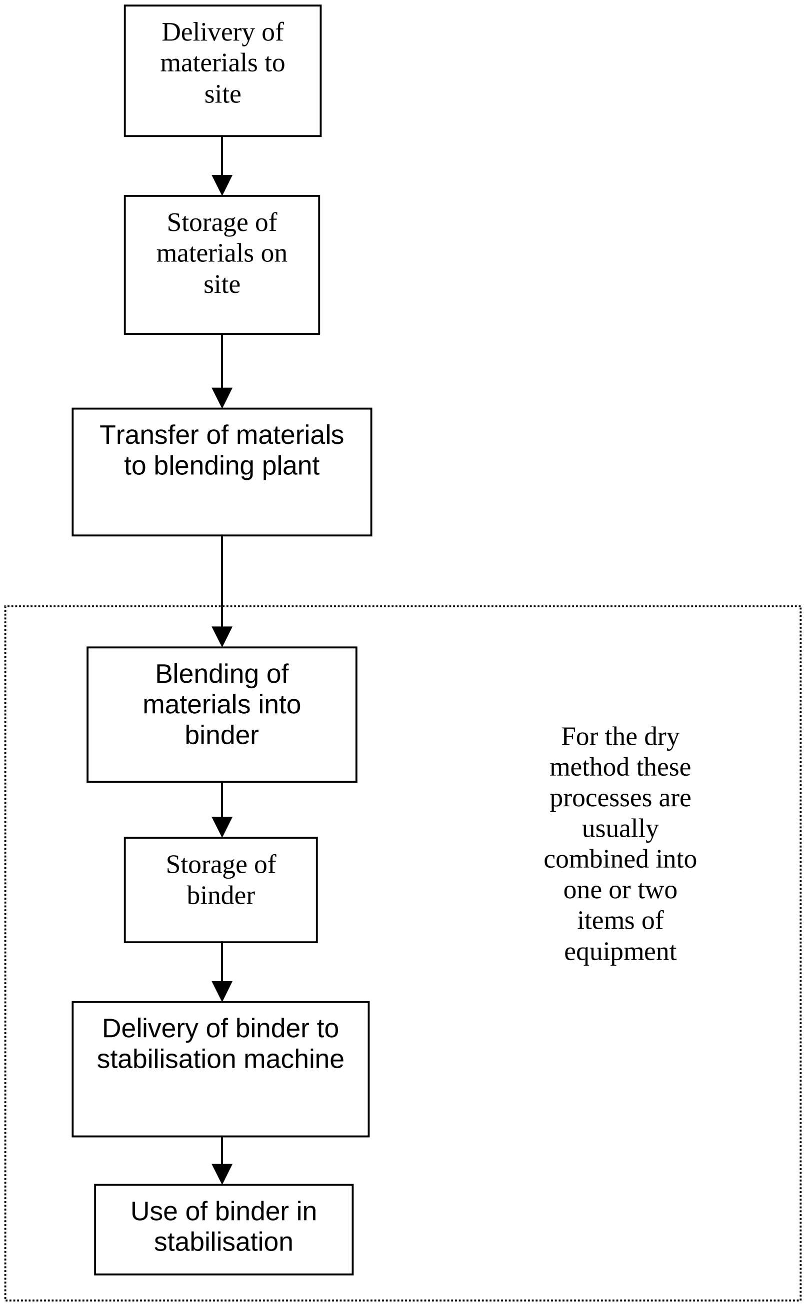


Figure 7.7. Flow chart for binder production and use.

In the case of the mass stabilisation process the binder is injected into the soil in the same way as for the column mixing but the mixing blades are in the form of a propeller on an hydraulically controlled arm. This enables the angle of the propeller and its depth to be altered by the machine operator to complete the mixing.

Deep dry mixing in columns
For the deep dry mix method the column diameters vary from 1.0 to 1.5 m for Japanese equipment to 0.5 to 0.8 m for Scandinavian equipment. The torque required by the mixing pipe and blades is typically 6 to 50 kNm at 150 rpm to 50 rpm.

Columns can reach down to 30 to 40 metres for the largest installation rigs. The rpm-value for Scandinavian equipment is typically 120 to 200 rpm. The lifting speeds in marine sensitive clays are usually around 15 to 30 mm per revolution. Thus, a 10 m long column may be constructed in about 4 minutes, which makes the method very cost effective for such soils.

The amount of binder is usually in the range 80 to 120 kg/m^3 in marine clays, for field strengths (c_u) of 40 to 60 kPa, whereas for organic soils a dosage of 250 to 350 kg/m^3 can be required for field strengths (c_u) of 100 to 150 kPa.

Deep wet mixing in columns
For the wet mix method the columns can be up to 1.2 m diameter and so the torque of the mixing pipe and blades can be up to 160 kNm with rotations at 15 to 20 revs/min and feed rates of 50 cm/min. The binder water slurry flow rates are generally around 35 to 70 litres/min.
The amount of binder is typically in the range of 300 to 400 kg/m^3 in soft organic soil to give a field strength (c_u) of 100 to 150 kPa.

Mass mixing
Mass stabilisation is a relatively new soil stabilisation technology. Here a block, typically 3 to 5 m deep, is thoroughly mixed with a dry binder transported by compressed air. This technique is well suited for the stabilization of organic soils, as for example peat and organic soils.

When the dry method is used, which has so far been the case for mass-stabilisation, the equipment consists usually of a pressurized binder container and a digger with an exhaust pipe and a propeller mounted at the end of the pipe. The operator injects the binder into the soil in such a manner that the binder is equally distributed and mixed with the soil. Usually a volume corresponding to 8 to 10 square metres in plan and 3 to 5 metres in depth is mixed in one sequence. For successful mixing in very soft ground the working blanket has to be removed along with the geotextile and replaced after mixing.
The amount of binder is typically in the range of 200 to 400 kg/m^3.

When the prescribed amount of binder is mixed into the volume treated, the mixing proceeds by moving the rotating propeller through the soil-binder mix, in order to obtain a homogeneous mixture. This process takes usually around 1 hour for around 100 m^3. The post mixing of the soil volume is very important, since to little mixing may result in a very inhomogeneous soil structure, with large chunks of very stiff material surrounded by soft, remoulded untreated soil.
Mass-stabilised areas should be loaded with a surcharge/working platform with a thickness of 0.5 to 1 m immediately after the completion of the mixing. In this way the remaining air from the mixing is removed and the final strength will be increased.

7.3.4 Sequence of mixing, plant positioning

The sequence of mixing for the deep column mixing will need to be adjusted to suit each specific site conditions but in general the most efficient sequence is to work the stabilisation machine within its radius of operation as much as possible before it is moved. Most machines will have a limited angle of slew for maximum stability while mixing. A typical sequence for deep mixing in columns is shown in Figure 7.8.

In the case of mass stabilisation the sequence is to stabilise a mass of soil in a block, within the radius of operation of the machine, of about 2 m by 4 m in plan with the stabilisation machine working close to the long side of the block. In this way several blocks can be worked sequentially after removal of the working blanket, and replacement after mixing so having a rolling programme and increasing production.

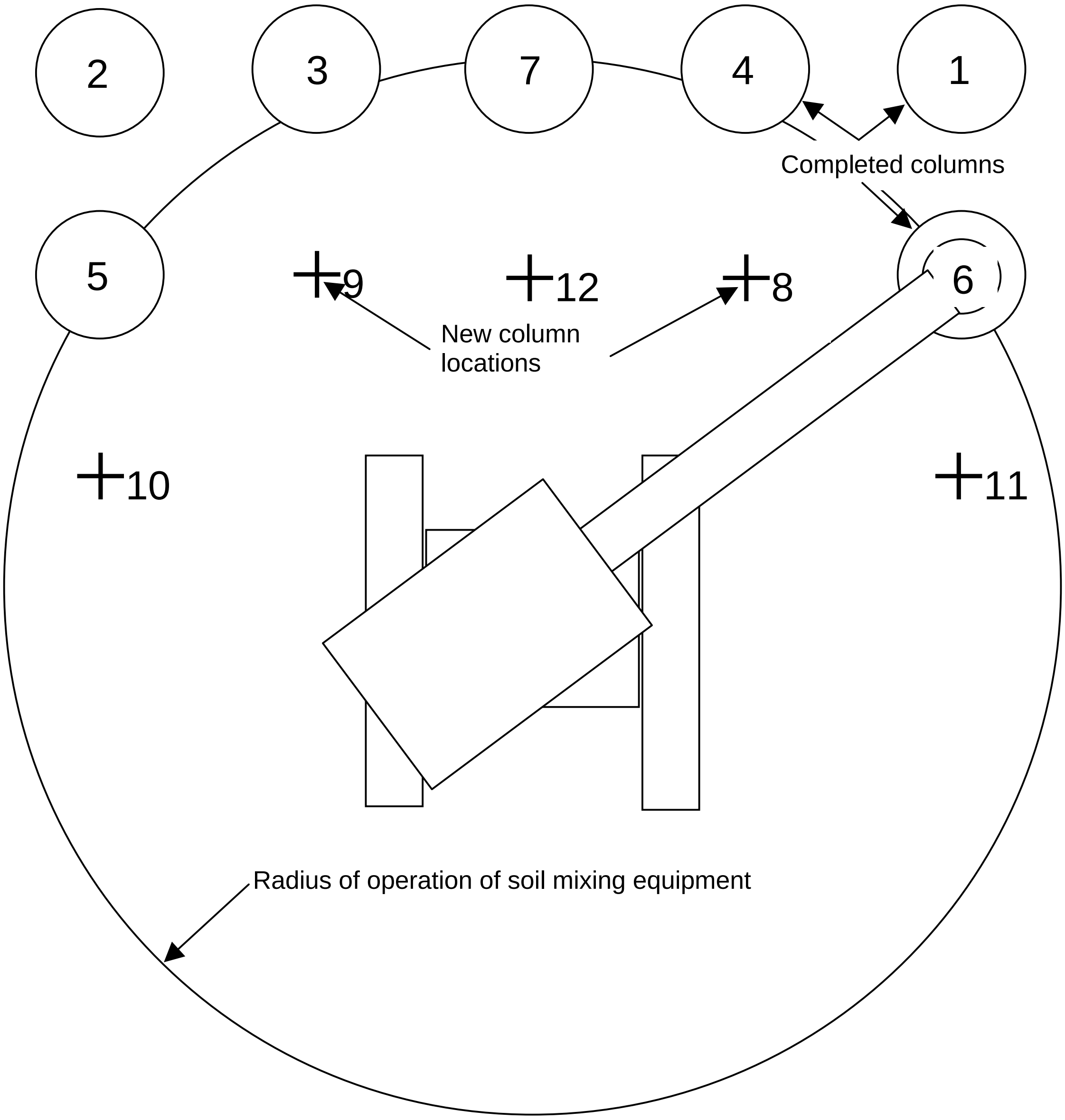


Figure 7.8. Sequence of construction for deep soil mixed columns.

7.3.5 *Production rates*

The production rates will vary depending upon the diameter of column mixed, the power of the stabilisation machine and the in situ strength of the soil. Table 7.1 below gives guide values to assist in estimating production rates.

Table 7.1. Guide values of the volume of soils that can be stabilised per hour by the different processes.

Process	Typical depth of treatment (m)	Volume of soil treated/hour (m/hr)
Deep dry mixing in 0.6 m dia columns	20	15 to 20
Deep wet mixing in 0.8 m dia columns	20	12 to 20
Mass stabilisation	6	100

7.3.6 *Effect on nearby structures*

The most likely effect on nearby structures is from heave during the deep mixing. In the case of deep dry mixed column a 5 to 10 cm heave is not uncommon within 0.5 m of the edge of a column during stabilisation work in soft clay. For deep wet mixing with high dosages and high slurry pressures heaves of up to 0.75 m have been measured. However these heaves are local to the columns and would only be a problem if the stabilisation was within one column diameter of a building foundation.

For mass stabilisation the greatest effect on a nearby structure would occur at the completion of an individual block of stabilisation. This is the point when the stabilised soil has the lowest strength and so gives the lowest lateral support to the surrounding ground. Foundation loads from and existing adjacent building could at this point induce a failure into the stabilised mass.

7.4 Monitoring and instrumentation

It is evident that instrumentation for monitoring the stabilization process carefully is very important since the stabilization process itself seldom lends itself to direct inspection. The amount of binder injected in a certain soil volume, as well as the geometry and homogeneity of the stabilized soil volume, whether it is columns or mass-stabilisation, must be evaluated by indirect measurements of binder use, slurry flow, or similar.

The technical problems related to monitoring are more pronounced for the dry than for the wet method. The binder contained in a flow of slurry is easier to measure than binder contained in a compressed air stream. Therefore, the weight loss of the binder storage tank is usually used as a measure of binder used when the dry method is used, whereas direct measurement of flow is more common for the wet method.

Monitoring continuously the weight of a binder storage tank as the dry binder is used is usually made by means of load transducers. In order to cancel out dynamic forces caused by vibrations of different pieces of the equipment used, 20 readings are taken each second and the mean value computed at a given instant giving an average of a large number of readings.

The change in weight is one of the main parameters to of the monitoring the process. The other is the depth of the exhaust nozzle. The depth is usually measured by means of a rotating wheel with a transmitter that gives a fixed number of digital pulses for each revolution of the wheel. The rolling wheel either bears on the mixing pipe or is connected to it by a cable. As the mixing pipe descends the cable turns the wheel and pulses are sent to the recording equipment. A calibration of the pulses allows accurate depth measurement of the mixing pipe.

For the wet method the quantity of each binder material needed for each batch is weighed as it is added to the measured water volume in the mixer. This process can be made easier with ready batched or pre weighed bagged materials.

Other signals used for monitoring the process are mixing tool rotation speed, lifting speed and force and engine torque. The value of these parameters are obtained from the base machines control instrumentation. All input signals are processed and presented in a clear display to the operator as well as stored on magnetic media, for example a 3.5” floppy disk, for further processing. It is important that the information is presented to the operator in a user-friendly way, making it easy to continuously provide a clear, comprehensive picture of all the components taking part in the process. For example the amount of binder in the storage tanks can be given both in numeric and graphical way, in a manner giving the operator an easy to read picture of quantity of binder remaining and the display can provide information about the zones where insufficient binder was added.

The data collected can be processed on site and the results presented to the client, serving as a base for quality control, verification and invoicing. Further, the data can also be included in the database, which can be used to produce production statistics and other useful information of the equipment and processes used.

A reference procedure for the installation techniques is included in Annex A and examples of the outputs and displays during production of the deep mixing are given in Annex B.

7.5 Environmental measures

7.5.1 Safety and health

Some binders may be harmful to health, as for example quick lime, which may cause damage to unprotected eyes and skin. Although operators and others in close contact with the process are most vulnerable to this, also humans not directly involved in the work may be in danger, as for example pedestrians passing close to a site where soil stabilisation is using potentially dangerous binder agents.

Further, large pressurized tanks must be inspected regularly in order to detect imperfections or damage that may result in decreased safety against unexpected behaviour, in worst case an explosion. This risk is most pronounced where such equipment is used where sufficient control of the equipment is not performed.

It is essential therefore that the appropriate measures are taken to mitigate the risk to the safety and health of personnel. The risks can be listed and rated in a risk assessment for the site works. An example of a risk assessment is given in Annex C and while this does not cover all risks is intended as an illustration of the risk assessment process.

Noise and vibration is usually not an issue where soil stabilisation is made. The equipment produces, in normal operation, much lower emissions then most other foundation equipment, as for example pile driving machines (BS 5228-1:1997, BS 5228-2:1997, BS 5228-4:1992).

Another environmental risk may emerge from the surface heave produced injecting pressurized air or slurry into the soil. There are examples where a heave up to 0.75 m has resulted from using high jet pressures with high (> 0.5) ratios of treated area to column area. However, usually the heave eventually produced is smaller, rarely more than 10 cm. Nevertheless, also such a limited rise of the ground must be taken into consideration where motion sensitive structures in the ground are present, as for example old water linings.

7.5.2 EC Ground water directive

The EC Ground Water Directive indicates a list of the main pollutants, will restrict the types of binder that can be used. However the rigorous application of this directive will stop most construction involving cast in place concrete and a modification to allow member states dispensation for construction has been tabled (March 99). This dispensation will probably include measures to control and monitor the effects of concrete and mixed soil on the environment. However the effect of the Directive and subsequent amendments and Member States national supplementary authorisation for use of construction materials in contact with the ground water need to be adhered to.

Dutch legislation, for example, cites the stabilised soil as a new material as buried in the ground and so should be subjected to:

- availability tests: how much contamination is in the new material;
- leaching tests: how much contamination will leach out of the new material under the test conditions.

As the new material is the stabilised soil it includes the natural soil which in the case of organic soils can have a high sulfate content. The mixed soil could therefore fail the leaching test because of the natural soil and not because of the added binder.

Threading the cable up the drill pipe.

Fixing the blade in space.

PORT ready for installation.

Figure 7.9. Attaching the PORT cable and blade to the deep mixing machine prior to installation.

7.6 Quality Assurance

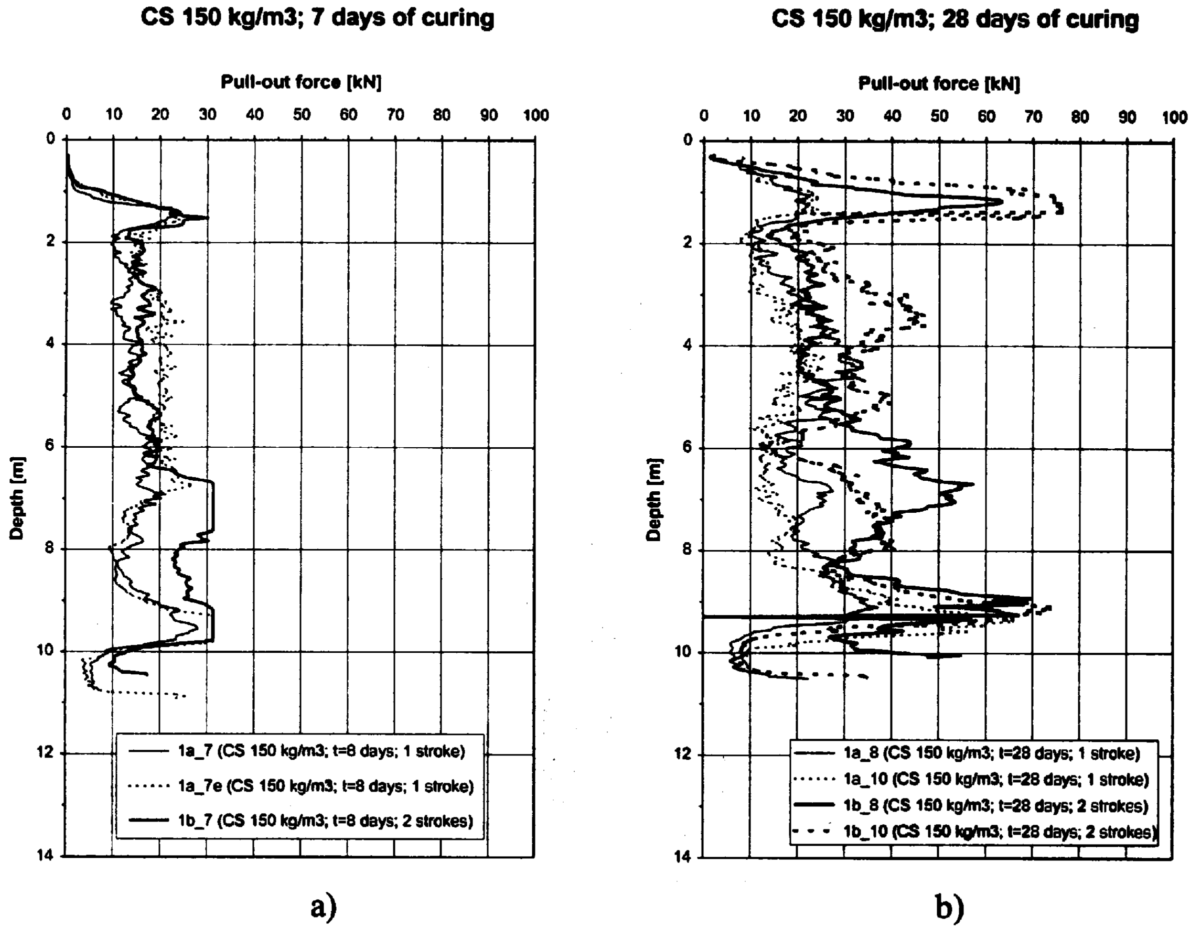
Quality assurance can be achieved through production controls with data records, post construction testing and performance monitoring.

7.6.1 Production Controls

Modern soil mixing equipment makes extensive use of computers. Computers control the mixing parameters (such as rotation rate, feed rate, binder feed) to achieve the design values, in many cases without operator intervention. The same computers are also used to monitor the parameters and display the data for the operator and store the data for later analysis. This data is essential for documentation of production on site to enable rapid comparison with the design. Typical outputs are included in Annex B.

7.6.2 Post construction testing

As mentioned above, QA rests to some part on data monitored during the mixing process. However, the development of strength and the improvement of deformation characteristics of the stabilised soil after the mixing can not be determined by data collected during the manufacturing stage. Instead the completed stabilised soil column or stabilised mass must be investigated.



Results from the pull-out resistance tests in cement-slag columns with 150 kg/m³ binder.
a) 7 days curing time
b)28 days curing time

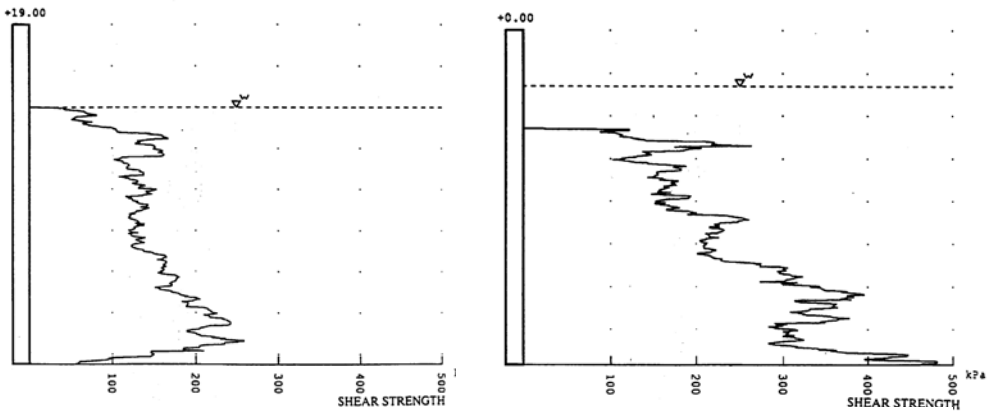
Figure 7.10. Examples of PORT results from soil mixed with cement – slag binder in columns at 7 days and 28 days.

Columns made by the dry method in soft clays are, within 28 days of construction, usually soft enough to be tested by means of pull out resistance tests (PORT) or penetration testing such as cone penetration testing (CPT) or dynamic cone penetration testing (DCPT). Columns made in heterogeneous or soils with sandy layers can produce very strong portions of the columns which will prevent the PORT or CPT tests being completed. In the USA the pressuremeter has been used successfully to test column quality.

The PORT works by pulling a specially designed blade/vane (projected area 15 mm by 500 mm), previously installed below the tip of the column, upwards through the column. The load required to pull the blade through the column has been correlated to column strength. The blade or vane with its loading cable are installed by the mixing machine prior to making the column (see figure 7.9). The blade is connected to the ground surface by means of a cable passing through the length of the column. At a specified time after mixing a pulling force is attached to the wire and the pull out force is measured. The strength of the columns (c_u in kPa) is calculated by multiplying the pull out force (F in kN) by a factor, typically 10. It should be noted that the pull out test gives a mean value of the strength of each level of the column. Soft spots in a column may therefore not be detected as they can be masked out by adjacent stronger material. A column tested with the specially designed blade/vane is disturbed. For applications with vertical loading, e.g. under a fill/an embankment the tested column is used. For other application the disturbance of the column should be considered. Examples of PORT data are given in figure 7.10 where cement-slag was used as a binder at a dosage of 150 kg/m3 and the tests show the increase in strength between 7 and 28 days of soil mixing.

A penetration test such as a CPT Lunne et al (1997) has the disadvantage that the tip tends to deviate out of the column after 5 to 7 metres. Therefore penetration testing can be of limited value as a validation tool, especially for relatively long and strong columns. This tendency to deviate can be overcome by pre-boring and starting the penetration test from the base of the pre-bored hole. Figure 7.11 shows CPT results from tests on cement – lime columns at 1 month and 6 months after mixing. While the columns are obviously at different levels the increase in undrained shear strength, calculated from the CPT, is significant at all levels.

Site: Kivikko: Cement/lime binder at 120kg/m^3



a) 1 month after mixing *b) 6 months after mixing*

Figure 7.11. Examples of CPT results from soil mixed with cement – lime binder in columns at 1 month and 6 months after mixing.

The problem of deviation also exists for core sampling of column material. The core drill hole has a tendency to deviate and leave the column moving out into the surrounding soil before the column tip is reached. Further, the column soil mix material is often not homogeneous and isotropic, so that many core samples have to be taken and the location of the samples determined in order to get a comprehensive picture of the quality of the column.

For column of limited length is possible to recover the complete column and make the sampling from the column taken to the surface. However, this is a costly operation and it of course also destroys the column. For larger projects in soils not stabilised before, the clients generally prescribe complete column recovery to assess the quality of the mixing. Using this test method, all properties, as for example homogeneity, anisotropy, and to some extent even geometrical shape, can be tested. For stabilisation down to 3 to 4 m an excavation next to the stabilised soil will allow in situ inspection. Such excavations will need to be properly supported and ventilated for health and safety of staff carrying out the inspection (BS 5930:1999, BS 8000-1:1989, BS EN 1536:2000).

8. Inspection

It is recommendable to divide the route for the rail or road embankments into characteristic geotechnical areas. In each characteristic area, tests should be performed to determine the characteristic soil layers, the requirements for the binders, the dimensions of the stabilised soil columns and/or mass stabilisation and the lay-out of the design.

The inspection of the stabilised soil columns - and mass stabilisation - should at least focus on the achieved properties for strength, deformation, elasticity, density, permeability and leaching.

Per test-site:

- Perform the soil investigations as described in chapter 5.

- Perform binder tests in the laboratory as described in chapter 6. Search for binder mixes that will meet 3-5 times the design requirements for strength.

- Perform field tests at the different test-sites:
  - Install a sufficient amount of stabilised soil test columns. Mix the soil and binders with the equipment to be used in the final construction. Record the amount of binder and the mixing energy per unit length of column as described in chapter 7. If possible use several mixing tools and mixing energies. Install a sufficient amount of devices for Pull Out Resistance Tests (PORT).
  - Take samples of the wet soil-binder mix. Test these samples under laboratory circumstances for strength, elasticity, permeability and leaching properties determining the design and the requirements for the environmental impact.
  - Take core samples of stabilised soil columns. Perform tests (hand-vane tests, uni-axial compression tests) to determine the strength, elasticity, permeability and leaching properties.
  - Determine in the test columns the in situ strength and elasticity properties. Perform PORT tests and/or the pressiometer tests and/or vane tests and/or CPT-tests.
  - If necessary, adjust the specifications for constructing the test-columns.

- Decide on the final design: type of binder and lay-out of the stabilised soil columns:
  - choose type and amount of binder and the mixing energy in combination with the mixing tool;
  - if necessary, adjust the relevant dimensions in the lay-out of the first design, including the construction planning, including possible pre-loading of the soil stabilisation etc.

- Construct the soil stabilisation for the test-embankment at the test site
  - Install sufficient PORTs during construction.
  - Install sufficient pore water pressure devices in the subsoil.
  - Install sufficient devices in the subsoil to monitor horizontal and vertical soil displacements.
  - Perform PORT tests, pressiometer tests and/or vane-tests and/or CPT's in the stabilised soil columns in order to determine the in situ strength and the in situ elastic parameters.
  - Determine the density of the stabilised soil columns in order to get an insight in the homogeneity of the stabilised soil column over the vertical.
  - If necessary, adjust the design and lay-out of the stabilised soil columns plan based on the observed in situ strength and the in situ elastic properties.
  - Construct the test embankment.
  - Observe pore water pressures, settlements and horizontal soil displacements.
  - Determine the load-settlement curve and time-settlement curve. Calculate future behaviour: extrapolation based on back-analysis. The back-analysis is based on the observations in the test field. Draw conclusions and adjust final design if necessary.

- Construct the final soil stabilisation for the total characteristic section and do this in principle as on the test site (monitoring on a less intense scale)
  - Design of monitoring programme.
  - Construction of the embankments in the characteristic section.
  - Monitoring (applied load, pore pressures, settlements, horizontal deformations).
  - Compare observations (monitoring) with predictions and take action if necessary.

- Steps to be taken when stabilisation does not meet requirements regarding stability or settlement behaviour

  - determine the effect of additional pre-loading and decide whether it would help.
  - study the possibility of inserting extra columns and/or mass stabilisation through the embankment body (or remove embankment body temporarily).
  - extend the construction time.
  - other measures.

- Additional inspection
  - Perform CPT's (possibly using stepwise preboring) in stabilised soil (columns/mass stabilisation) maybe during and short after construction in order to determine continuity and homogeneity of the stabilised soil column.
  - etc.

ANNEX A RECOMMENDED PROCEDURE FOR INSTALLATION OF DEEP AND MASS SOIL MIXING

Introduction

To ensure that the working methods and results from the equipment monitoring system of the field tests from each site can be compared, it is important that a reference procedure for this installation technique is developed. This report proposes such reference procedure for the installation. Also suggested is how to adjust and modify the existing equipment.

General

Site documents shall be prepared for each field test site describing the test site instrumentation, installation technique for column and mass stabilisation and also describing the monitoring and control systems.

Test site instrumentation supposed to be active before, during and after installation of soil stabilisation, shall be installed at the site. Although such instrumentation is to be defined by other task groups, some instruments are mentioned below, as for example:

- pore pressure meters (between columns as well as into the columns)
- earth pressure meters
- inclinometers
- surface heave
- settlement gauges
- temperature gauges
- pore gas pressure meter for measuring in and between columns (if possible)
- measuring of pollution, vibrations and dust emission.

and other monitoring equipment, as specified in test site documents.

As a part of the design, suitability tests have to be done, as far as the are not available for the installation method in similar subsoil.

Soil investigation shall be carried out before and after installation as outlined in the test site measurement description (task 2).

Noise and vibration levels (dBA) 10 and 50 meter from the rig at representative occasions of operation shall be measured and documented.

All documentation and monitoring shall use the English language (British English) and the SI-system.

A.1 Installation procedure

A.1.1 Column stabilisation

A.1.1.1 Pre-installation procedure (dry and wet column methods)
Before installation of column, the following conditions shall be checked and documented:

- Data for binders
  - production date and delivery date
  - storage conditions
  - transportation
  - storage temperature
  - test to confirm the binder quality
  - binder components
  - water type/quality

- Machinery equipment
  - type of equipment
  - design of mixing tool
  - all other relevant data

- Site description
  - location and site elevation level
  - geotechnical conditions
  - weather conditions during installation
  - photos from the site
  - state of eventual soil contamination

- Column data
  - diameter, m (usually 500-800mm)
  - amount of binder, kg/m or litre/min
  - mixing energy, J/m^3
  - lifting speed, mm/s and mm per revolution
  - rotation speed, rpm
  - length, m (up to 25m)
  - column top level (elevation)
  - column tip level (elevation)
  - feeding pressure, max. MPa (applies to both wet and dry method)
  - exhaust pressure (inside Kellybar) at mixing tool level
  - water to cement weight ratio (for wet method)
  - ratio of grout and additives

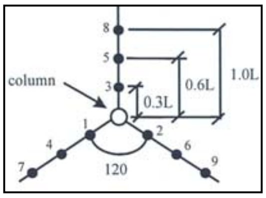
A.1.1.2 Dry method (Scandinavian equipment)

1. The mixing tool is pushed vertically into the soil down to the prescribed depth. If rotation is used, the rate of rotation speed shall be registered. The time for pushing as well as the depth of penetration shall be documented.

2. The mixing tool is lifted and simultaneously rotated. During lifting, the binder, usually dry cement and lime, is injected to soil. The injection is made from the centre of the mixing tool by rotation for the mixing tool wings. The amount of binder per cubic meter and also the supplied energy per cubic meter shall be prescribed. Continuous monitoring shall be carried out automatically for:

	Typical values
- binder output, kg/m and kg/m^3	16-50 kg/m
- mixing energy, J/m^3	
- lifting speed, mm/s and mm per revolution	20-50 mm/s
- rotation speed rpm	100-200 rpm
- feeding pressure at rig	0.2-0.7 kPa
- exhaust pressure (inside Kellybar) at mixing tool level	0.2-0.6 kPa

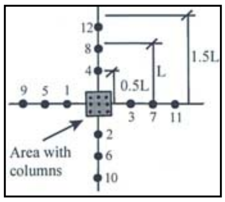
3. The feeding pressure shall be released after installation, surface heave shall be monitored both around one single column (see figure A.1a) and around the whole stabilised area (see fig. A.1b). The accuracy shall be + 1 mm. One point each 200 m^2 will be sufficient.



● = leveling points

a) L= column length

a) Around one column



● = leveling points

b) L= column length

b) Around an area with columns

Figure A.1. Monitoring of surface heave before and after installation.

4. For some columns, it is recommended that the temperature be measured in a number of columns. However, this is a matter for task group 4.

A.1.1.3 Wet method (slurry)

1. The mixing tool is inserted (bored or pushed) vertically into the soil down to prescribed depth. While the mixing tool is pushed down, injection of slurry could be made. If rotation is used, the rate of rotation speed shall be registered. The time for pushing as well as the depth of penetration shall be noted. If injection of slurry is made, the amount shall be noted as well as the mixing energy (J/m^3) and the rate of penetration. If the mixing tool is rotated with injection at the bottom level for some time, this has to be documented (see time-output and time-lifting speed curves, fig. A.3).

2. During the injection of slurry, continuously monitoring shall be carried out automatically for:

	Typical values
- output of slurry, litres/minute	100 to 250 litre/min
- input pressure at machine, kPa	max. 20 bar
- output pressure, kPa (if possible)	0 to 10 bar
- lifting speed, m/s	0.1 to 0.5 m/s
- rate of rotation, rpm	10 to 20 rpm

3. The amount of slurry overflowing at the top of the column shall be measured during installation until the slurry flow is cut off.

4. Starting before and up to 48 hours after installation, surface heave shall be monitored both around one single column (see fig. A.1a) and around the whole-stabilised area (see fig. A.1b). The accuracy shall be + 1mm. One point each 200 m^2 will be sufficient.

5. If cement is used the water to cement weight ratio shall be documented (typically in the range 0.5 to 2.0). However other binders such as lime and/or bentonite are also used depending on the application.

A.1.1.4 Visual documentation

Videotape recording and photo’s, covering the complete installation process, shall be taken.

A.1.1.5 Supervision of work

A site superintendent shall be apparent who will be responsible for the work mentioned above and installation. The site superintendent shall approve all documents by signing with his name, the current time and date.

Calibration data for all measuring equipment shall also be documented. The site superintendent who must be an authorised person shall sign the document. The superintendent should be experienced.

A.1.2 Mass stabilisation

A.1.2.1 Pre-installation procedure (dry and wet methods)

Before installation of mass stabilisation, the following conditions shall be checked and documented:

- Data for binders
  - production date and delivery date
  - storage conditions
  - transportation
  - storage temperature
  - test to confirm the binder quality
  - binder components
  - water type/quality

- Machinery equipment
  - type of equipment
  - design of mixing tool
  - all other relevant data

- Site description
  - location and site elevation level
  - geotechnical conditions
  - weather conditions during installation
  - photos from the site
  - state of eventual soil contamination

- Data for column stabilisation (before the mass stabilisation)

- Data for mass stabilisation
  - amount of binder, kg/m^3 or litre/min
  - mixing energy, J/m^3
  - rotation speed, rpm
  - depth, m (usually 3-4 m)
  - feeding pressure, max, MPa
  - slurry, water to cement weight ratio (for wet method)

A.1.2.2 Dry method

1. A horizontal surface area not larger than 5 x 5 meter is marked by means of 4 sticks pushed into the ground.

2. The mixing agent is mixed uniformly with the soil down to the prescribed depth (3-4 meter) from surface (fig. A.2). The amount of binder (kg/m^3) and the mixing energy (J/m^3) shall be as defined in the site test description. The mixing pattern shall be as described in the test specifications.

3. While the mixing agent is pumped out into and mixed with the soil continuously monitoring shall be carried out automatically for:

	Typical values
- binder output, kg/m^3	100-400 kg/m^3
- input pressure at machine, kPa	0.2-0.4 kPa
- output pressure, kPa	0.2-0.5 kPa
- rate of rotation, rpm	100-200 rpm

4. After initial mixing with binder exhaust, remoulding of the soil volume is continued uniformly so that the prescribed mixing work is obtained for the complete volume. The volume is defined by the sticks and the depth of mass stabilisation. The remoulding pattern shall be carried out as specified in the specifications.

5. After mixing work is finished, a geotextile with sufficient bearing capacity and 500 mm gravel are placed on the stabilised surface (fig. A.2). At the discretion of the site superintendent, the geotextile could be excluded.

6. Compaction is made by a heavy roller as defined in test site description.

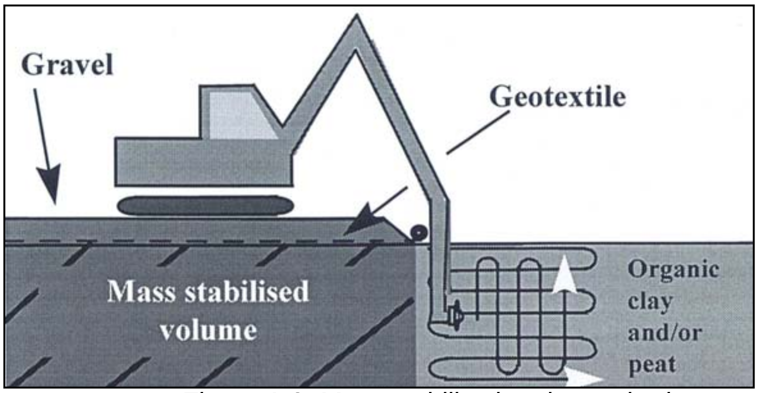


Figure A.2. Mass stabilisation dry method.

A.1.2.3 Wet method

1. A horizontal surface area not larger than 5x5 meter is marked by means of 4 sticks pushed into the ground.

2. The mixing agent is mixed uniformly with the soil down to the prescribed depth from surface. The amount of slurry and the mixing energy (J/m^3) shall be as defined in the test site description. The mixing pattern shall be as described in the test specifications.

3. While the slurry is pumped out into and mixed with the soil shall continuously monitoring with an automatic system be done of:

	Typical values
- output of slurry, litre/minute	100 to 250 litre/min
- input pressure at machine, kPa	max. 20 bar
- output pressure, kPa (if possible)	0 to 10 bar
- lifting speed, m/s	0.1 to 0.5 m/s
- rate of rotation, rpm	10 to 20 rpm

4. The amount of slurry flowing away from the test area shall be registered during installation until the slurry flow is cut off.

5. After initial mixing with binder exhaust, remoulding of the soil volume is continued uniformly so that the prescribed mixing work is obtained for the complete volume. The volume is defined by the sticks and the depth of mass stabilisation. The remoulding pattern shall be carried out as specified in the specifications.

6. After the mixing work is finished, a geotextile with sufficient bearing capacity and 500 mm gravel are placed on the stabilised surface. At the discretion of the site superintendent, the geotextile could be excluded.

7. Compaction is made by a heavy roller as defined in test site description.

8. If cement is used the water to cement weight ratio shall be documented (typically in the range 0.5 to 2.0). However other binders such as lime and/or bentonite are also used depending on the application.

A.1.2.4 Visual documentation

Video tape recording and photos, covering the complete installation process, shall be taken.

A.1.2.5 Supervision of work

A site superintendent shall be apparent who will be responsible for the work mentioned above. The site superintendent shall approve all documents by signing with his name, the current time and date.
Calibration data for all measuring equipment shall also be documented. The site superintendent who must be an authorised person shall sign the document. The superintendent should be experienced.

A.2 Development and adjustment of existing equipment for output of dry binder or slurry

In order to fulfil the required operation and monitoring standards outlined above, some adjustment and modification for all existing equipment is needed. The main points are briefly described below.

The amount of binder shall meet the specifications in the test description. That is that the specified amount of binder/slurry per soil volume shall also be output in the soil.

At the same time, the mixing energy shall be equal to the value specified for the test.

The binder amount and the mixing energy are evaluated from results of laboratory tests, and shall be specified in the test site description.

The output rate depends on the difference between the system pressure and the external pressure delivered by the soil at the level of the mixing tool. This means that the system pressure should be changed as the external pressure from soil and ground water varies, in order to maintain a constant rate of binder output.

For many types of existing equipment, a constant system output pressure is applied.
The lifting speed is varied in order to obtain the specified output of binder per soil volume. This results in different mixing energy for different soil strata. Therefore the mixing energy at different levels may vary considerably, thereby introducing a source of error in comparing results from different machine equipment.

In summary, the equipment used for all test installations shall be able to monitor system output pressure as well as external pressure (soil aggregate + water + gas). Further, the system pressure shall be possible to change depending on the external pressure. This shall be done automatically and the process shall be registered and documented by the monitoring system (see fig. A.3).

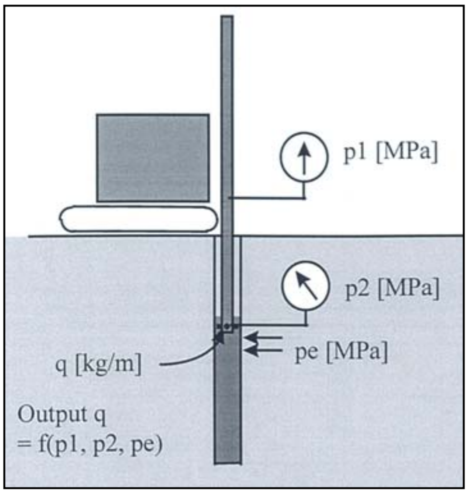


*Figure A.3. Internal and external pressures, p1, p2 and pe.
Binder output = q*

A.3 Development and adjustment of monitoring and control system

Many types of existing equipment do not monitor or report production data in a way, which is sufficient to satisfy the expected test specifications.

Monitoring
The following data shall be monitored automatically and continuously during the process of installation:
- amount of binder / flow rate
- lift speed
- depth
- revolution rate
- internal and external pressure
- applied energy (if possible)
- applied power (if possible)
- pushing and lifting force (if possible)

And possible also:
- amount of air
- temperature

All data shall be stored on a PC-card or similar. The data shall be presented on a graphical user interface to the operator in order to make it easy to adjust the installation process as necessary. It shall be possible to view all data as function of time and depth. All presented measured values shall be unchanged.

A paper copy shall be possible to print on site. The complete documentation shall be registered on the PC-card. The data on the PC-card shall be printed out on a separate PC. An example of a documentation layout produced from a PC is shown in fig. A.4 and A.5.

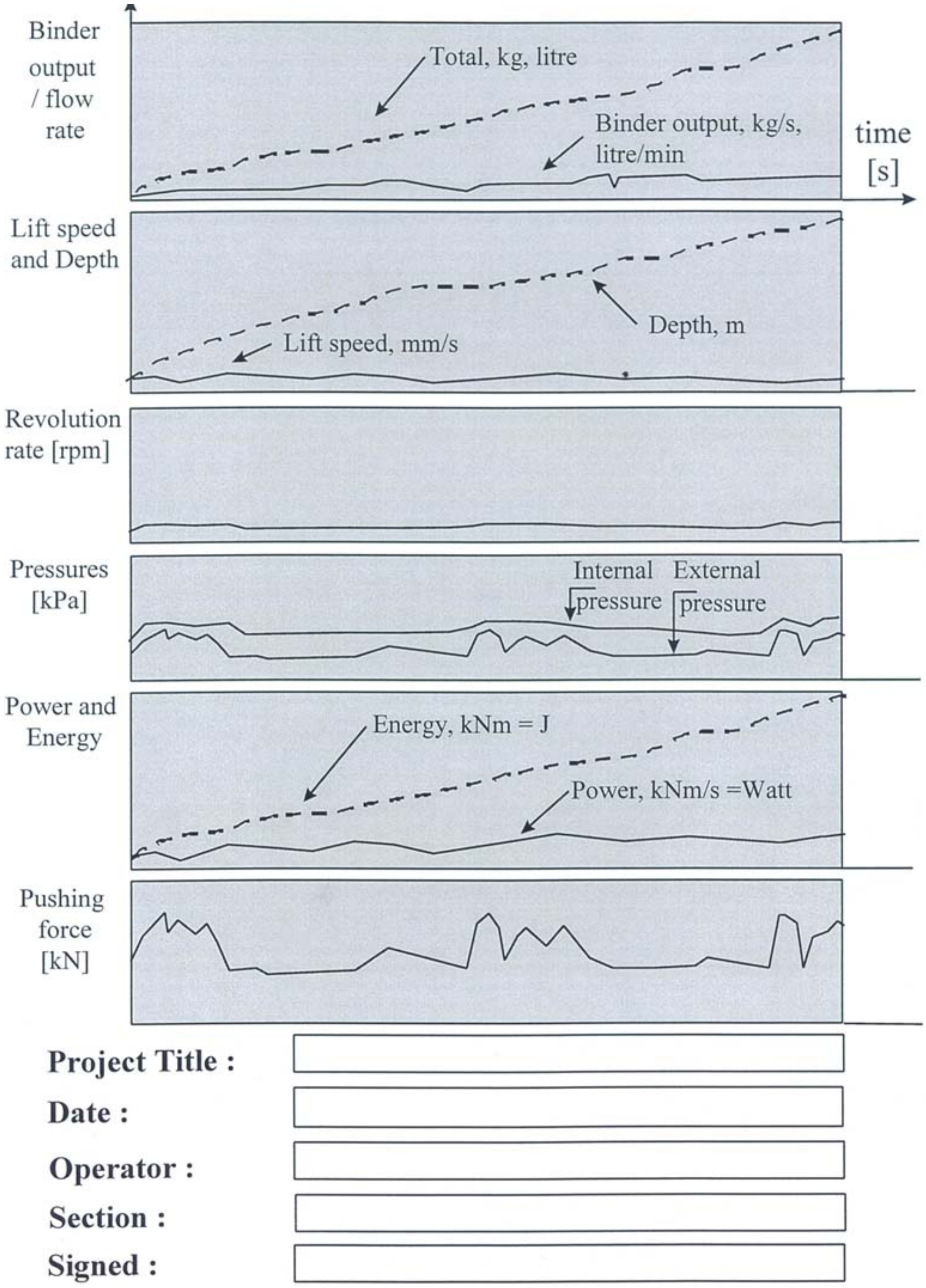


Figure A.4. Example documentation layout.

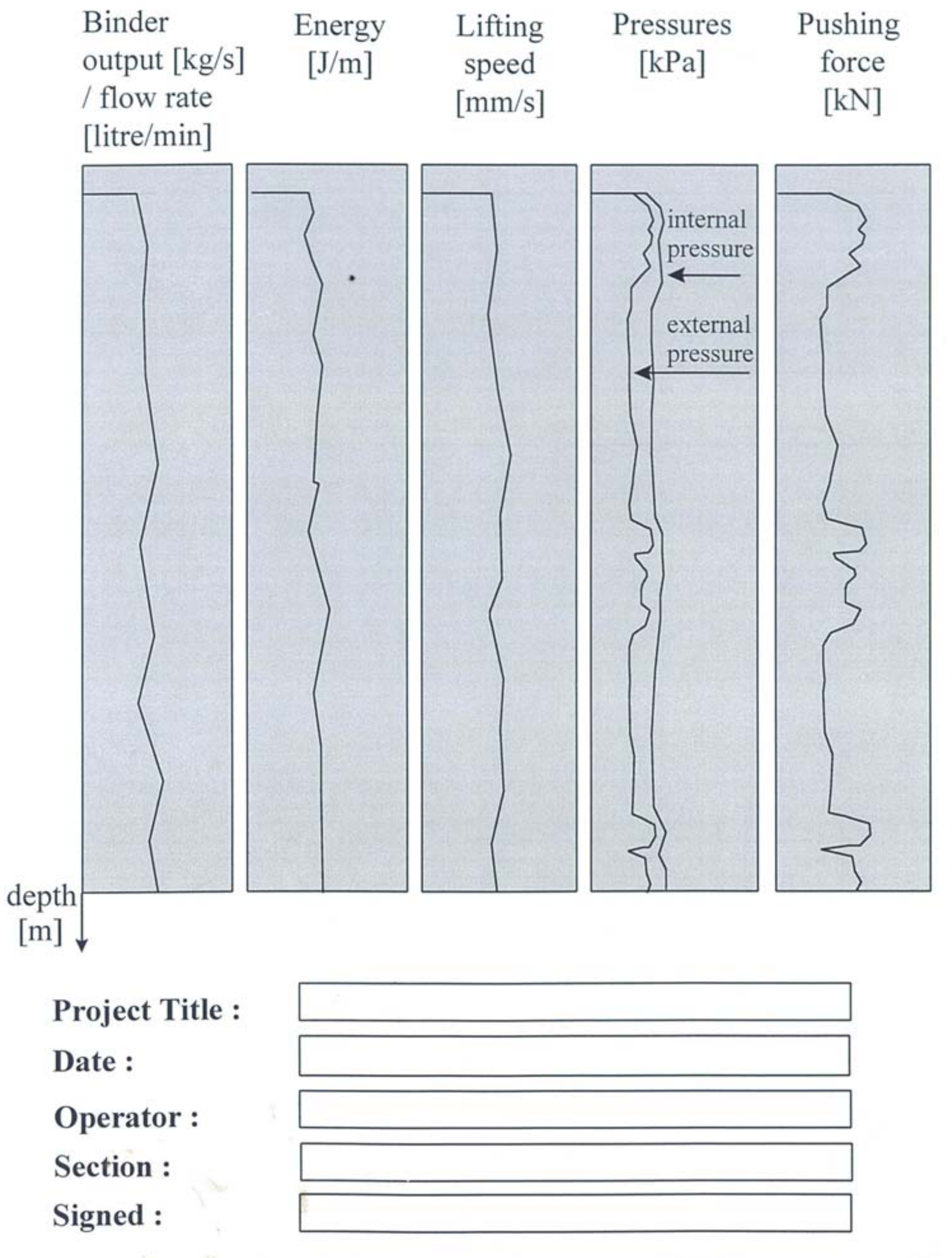


Figure A.5. Example documentation layout.

ANNEX B EXAMPLES OF MONITORING SYSTEMS AND THEIR OUTPUTS DURING DEEP MIXING PRODUCTION

An example of the monitoring systems for the soil mix process is that used by stabilator who have developed an advanced system which is now installed on their production equipment.

<u>Installation process</u>

The central verifying equipment in the soil mixing equipment are two computers. One computer gathers information from the machine and sends it to the other computer by communication. There the operator analyzes the installation process using the display consisting of graphics, indicators and numbers. Through this computer the operator also controls the installing process by starting and stopping it and, if necessary, making some adjustments.

Figure B.1 shows the display units as fitted in the operators cabin on the installation equipment. At the top there is the computer and its operating monitor with which the operator works. Below the computer there are two devices which enable the operator to adjust the equipment to comply with the requirements of the specification.

Figure B.1. The display units as fitted in the operators cabin on the installation equipment.

Operating monitor

The operating monitor, as shown in figure B.2, displays all data from the monitoring computer to the equipment operator. The binder supply tank condition, rate of binder feed are in the top left hand corner with current depth of mixing tool, tool rotation and supplied binder below. The supplied binder should follow the design line which has an upper and lower tolerance line. Other parameters such as lift speed and hose pressures etc. that the operator needs to be aware of are given on the right hand side. As the system is updated it checks the recorded parameters with the design parameters previously entered and if the recorded parameters are outside the tolerances the monitor changes the colour of the display for that parameter to warn the operator. The operator can then take appropriate action to bring the parameter back within tolerance.

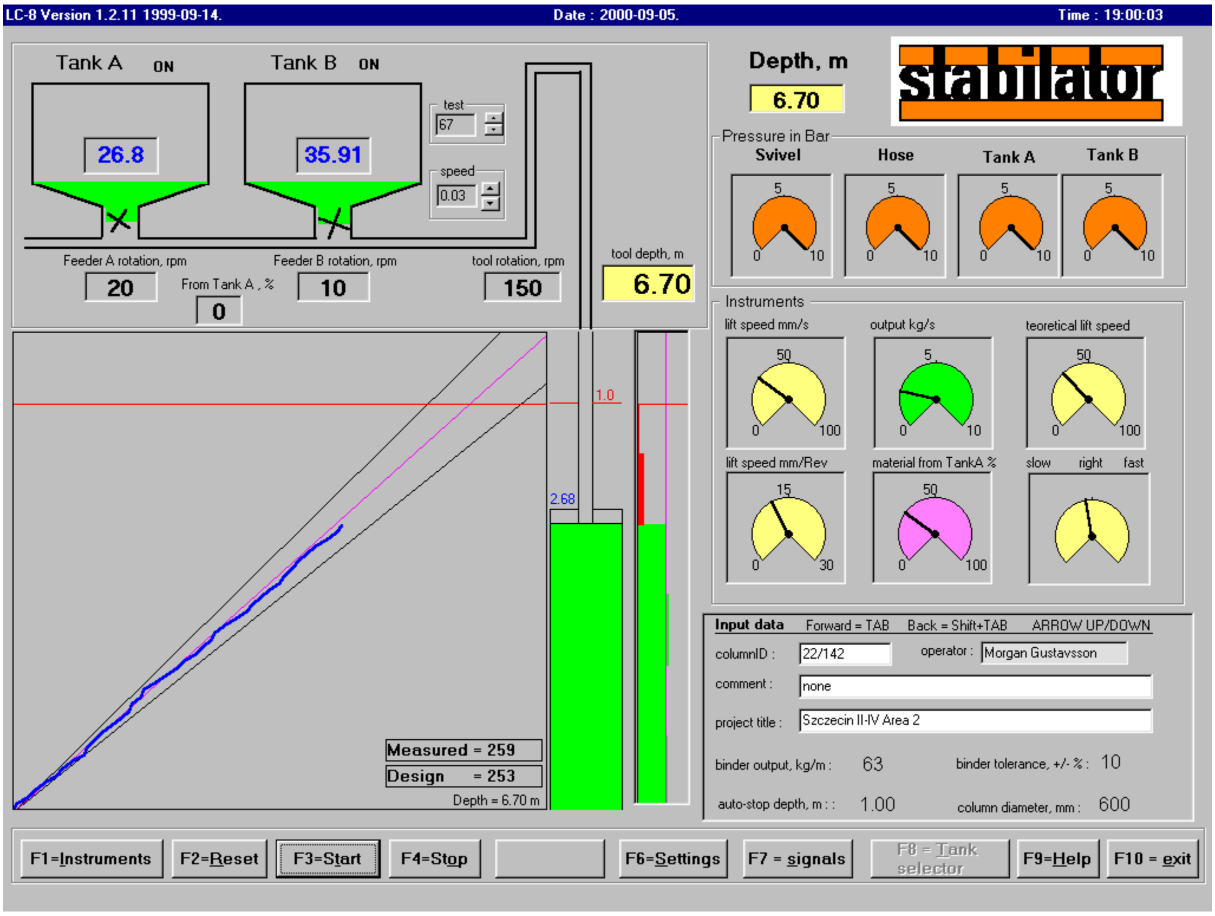


Figure B.2. Typical operating monitor display showing the progress of deep dry mixing in a column.

After a soil mixed column has been installed, the computer saves the installation information in text files. These files are used to produce outputs to show the installation parameters for each individual soil mixed column. Figure B.3 shows a series of graphs of the installation of column 102 as a function of time.

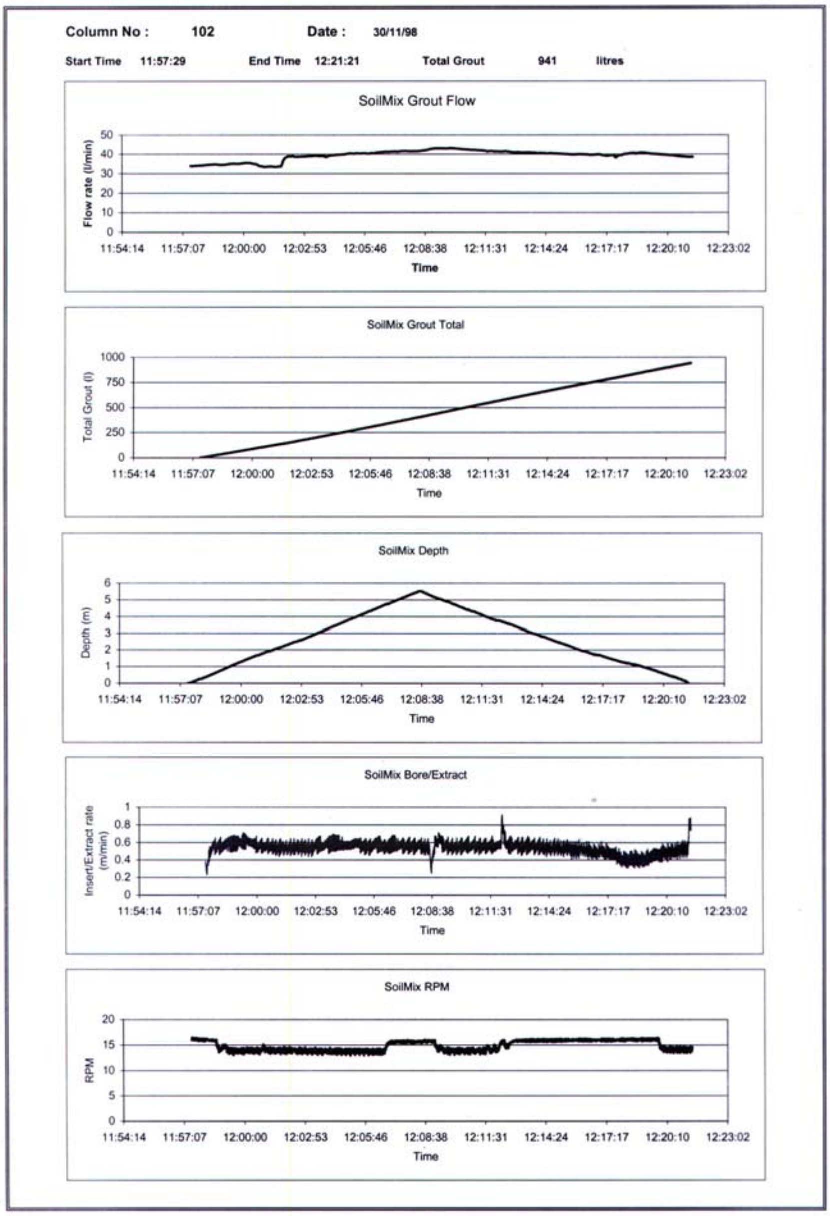


Figure B.3. A series of graphs of the installation of column 102 as a function of time.

Figure B.4 shows a typical daily log sheet for soil mixing. The daily log sheet shows the numbers of the columns mixed, their length, nominal diameter, time taken, binder slurry volume and binder mix. Additional data is given at the bottom of the sheet concerning the operatives, design parameters, mix design details and total material use.

Keller Ground Engineering
Geotechnical Engineering Contractors
Tel 01937 541118

KELLER
A DIVISION OF KELLER LTD

DAILY SOIL MIXING REPORT NO. 8

AREA Section C-C and D-D
CONTRACT Euro Soil Stab - Dartford
CONTRACT NO. 1.6648
CLIENT BRE / Keller
DATE 30.11.98

Column No.	Datum Existing GL Level (OD)	Depth to Top of Column (m)	Depth to Base of Column (m)	Column Length (m)	Nominal Column Diameter (m)	Insert Time (mins)	Lift Time (mins)	Total Time (mins)	Grout Volume (litres)	Testing grout cubes, U100s, insertion of double pipes, Etc.	Remarks Interruptions to mixing, Etc
60			5.5	5.5	0.9	14.0	12.0	26.0	1008	Mix 2	
67			5.5	5.5	0.9	14.0	12.0	26.0	1036	Mix 2	
74			5.5	5.5	0.9	13.0	11.0	24.0	982	Mix 2	
81			5.5	5.5	0.9	14.0	12.0	26.0	1034	Mix 2	
88			5.5	5.5	0.9	15.0	12.0	27.0	1022	Mix 2	
95			5.5	5.5	0.9	12.0	11.0	23.0	869	Mix 2	
102			5.5	5.5	0.9	12.0	12.0	24.0	941	Mix 2	
61			5.5	5.5	0.9	12.0	12.0	24.0	1000	Mix 2	
68			5.5	5.5	0.9	13.0	12.0	25.0	1102	Mix 2	
75			5.5	5.5	0.9	12.0	11.0	23.0	965	Mix 2	

WORK SUMMARY				COLUMNS			GROUT VOLUME	
	Nominal Dia. (m)	1.2	0.9	Nominal Dia. (m)	1.2	0.9		
	No. Today	2	16	Length Today (m)	11	88	Grout Today (l)	20209
	Previous No.	57	45	Previous Total (m)	221.5	247.5	Previous Total (l)	120287
	Cum. Total	59	61	Cum Total (m)	232.5	335.5	Cum. Total (l)	140496

OPERATING PARAMETERS						GROUT DESIGN DETAILS							
	Nominal Dia. (m)	Insertion Rate (m/min)	Lift Rate (m/min)	R.P.M	Grout Flow (L/min)		Mix No.	OPC (kg)	PFA (kg)	GGBFS (kg)	Bentonite (kg)	Water (litres)	Other (kg)
	0.9-1.2	0.5	0.5	16	40-70		1	400		400		400	
							2	200		600		400	

Name	Trade	Hours			Trade	Hours	Signed For
R Emerson	Driver	10					
A Walker	Mixer	10					Client
M Waddilove	Pump	10					
G Harvey	Driver	10	Time: Started	8.00	Finished	1800	Keller Ground Engineering

BLUE - HQ	YELLOW - CLIENT	YELLOW - CLIENT	WHITE - SITE

Fig. B.4. A typical daily log sheet for soil mixing site.

ANNEX C EXAMPLE OF A RISK ASSESSMENT FOR DEEP SOIL STABILISATION

DATE: ##/##/## **ASSESSED BY:** *Project Manager* **LOCATION:** *Any Site* **Page** 1

ACTIVITY: Deep in situ soil mixing

Operation	Hazard	Who might be harmed?	Risk Factor	Is the risk adequately controlled?	What further action is necessary?
Describe the operation(s) being assessed.	List hazards here (see note 1 and refer to Annex B).	List groups of people at risk from the hazards identified. (note 2)	Calculate the Risk Factor. (note 3)	List existing controls, or where the relevant information may be found. (note 4)	List the risks that are not adequately controlled and the action you will take where it is reasonably practicable to do so. You are entitled to take cost into account, unless the risk is high. (note 5)
Pedestrian access	Debris falling, equipment, oil or other spills, uneven ground, trailing pipes	Users, other staff, contractors	1	Instruction, wear protestive clothing.	Cone off working area to restrict access to users only
Use of vehicles,	Collision with pedestrians	Users, other staff, contractors	1	Warning signs, Instruction	Cone off working area to restrict access to users only
Manual handling	Lifting, lowering, pulling, pushing	Users	1	Instruction, users must attend manual handling course, use mechanical assistance where necessary.	None.
Working with contractors crane	Collision with suspended equipment, falling debris, Worn, faulty or wrong lifting attachments.	Users, other staff, contractors	1	Instruction, users must attend manual handling and slinging course, wear protective clothing.	None
Mixing of binders	Inhalation of dust, lifting bags of materials, lowering bags of materials, opening bags of materials	Users, other staff, contractors	1	Instruction, Manual handling course, wear protective clothing, use of mechanical assistance where possible.	Work in well ventilated areas
Storage and					

transfer of materials	Inhalation of dust, lifting bags of materials, lowering bags of materials, opening bags of materials, Escaping high pressure gas and gas driven particles	Users, other staff, contractors	1	Instruction, Manual handling course, wear protective clothing, use of mechanical assistance where possible.	Work in well ventilated area, Clean up contingency in place.

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5. BS 8000-1:1989 Workmanship on building sites. Code of practice for excavation and filling. British Standards Institute, London.

6. EN 791:1996: Drill rigs. Safety. British Standards Institute, London.

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8. EN 809:1998. Pumps and pump units for liquids. Common safety requirements.

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10. Lunne, T., Robertson, P.K., & Powell, J.J.M. (1997). CPT in geotechnical practice. Blackies, London.